“A Novel Parametric Scale for Determining Rehabilitation Progress in the Upper Limb”

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Abstract

The process of sensorimotor rehabilitation depends upon the clinical condition, age and circumstances of the patient and is unlikely to be continuous or predictable in nature. Mapping progress in conditions such as stroke, cerebral palsy and traumatic brain injury relies upon a variety of qualitative assessments, each resulting in different scales of measurement. Most current assessments are elaborate, specific to certain participants and/or stages of a condition, and subject to inter-rater and intra-rater variability.

A simple and reliable measuring system is required that can capture rehabilitation progress from an initial state through to complete rehabilitation. It must be believable, flexible, understandable and accessible if the patient is to benefit from its use.

Two-dimensional reaching tasks reflect movements made in typical therapies and activities of daily living. This thesis hypothesises that valuable parameters exist within positional and temporal data gathered from simple reaching tasks. Such parameters should be able to identify movement quality and hence measure state and progress during rehabilitation. They should correlate well with a variety of clinical scales to be meaningful and, as quantifiable measurands, they should be extendable beyond the range of established clinical scales.

This thesis proposes a novel solution for the assessment of upper limb rehabilitation. An affordable desktop computer assessment system was developed and used with juvenile patient participants (N=11) to compare simple desktop reaching parameters with a clinical scale. A control group of normal juvenile participants (N=10) provided baseline data.

The results indicated good correlation with the clinical scale based upon a weighted combination of pre-selected movement parameters. The methodology developed permits assessment against further clinical scales and additional participant groups allowing rapid, accurate, reliable and extendable assessments.

The potential for mass data acquisition from clinical and domestic settings is identified to support the development of further assessments and, potentially, new therapies to address limited therapist availability and innovative treatments.

Dedication

To my beloved parents:

Your unconditional love and faith in me have guided every day of my life and you were the inspiration and strength that I needed throughout my work on this thesis, Sadly, you did not see me finish this but I hope that you would have been proud of what I have achieved.

Thank you for all that you gave me in life and continue to teach me.

Acknowledgements

I am very grateful to Dr Simon Kometa for his generous and good-humoured support with the statistical methods and SPSS™ software used in this thesis. He has shown me the practical application of statistical methods to support my proposals and how to avoid the many pitfalls that I might have otherwise inadvertently located.

The generous contributions of time and advice from Janice Pearse before and during the clinical tests have been invaluable in helping me to develop a system that is both safe and effective for children to use, and suitable for therapists to apply. I am particularly grateful for the privilege of being able to watch such a caring professional achieve so much with children, never accepting that little can be improved for them.

The overwhelming attention to detail and enthusiastic work carried out by Ben Sherlock in the development of the software and electronic controllers has made the project possible. What started as a basic system has required repeated revisions, re-development of system components and complete system redesigns. Ben's generous and good humoured support and determination to solve all the software issues that were beyond my humble abilities have made this project very enjoyable.

My thanks to Professor Garth Johnson for his inspiration and early supervision before his retirement. It was a gentle introduction to a fascinating subject and his encouragement made my transition from commercial engineer to potential researcher so very interesting.

Dr Rob Forsyth has provided an invaluable medical counter-point to the engineering requirements for this thesis, as well as financial support for equipment and access to the all-important patient participants. His contributions are evident throughout this thesis and particularly in helping me to assess the "noisy" behaviour of humans as data sources in a medical context. The support that he provided in allowing and encouraging a work-hardened engineer to enter the subtle medical world is most gratefully acknowledged.

Professor Tom Joyce took over as my main supervisor when Professor Garth Johnson retired. My research and this thesis had stalled and needed significant invigoration and guidance and Tom selflessly agreed to help. Without his tireless support, subtle guidance and timely encouragement this thesis would not have been completed. I am forever in your debt.

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1 Introduction

1.1 Hypothesis

This thesis explored the following main hypothesis:

> ***"Simple movement parameters, obtained from varied but repeatable two-dimensional reaching tasks, can be used to establish a state of rehabilitation from which quantifiable measurements can be made to record progress."***

1.2 Guide to Thesis

The following sections describe the format and content of this thesis and are intended to guide the reader.

Chapter 1 - Introduction
The defining hypotheses, background motivation, principal activities and justification for a new automated rehabilitation measurement and therapy (ARMaT) prototype device are presented. The need for, and potential of, a unifying metric to describe a continuum of ability is introduced. Glossaries are offered to help the reader as there are several distinct themes and applications discussed in this project that span common engineering and medical subject areas.

Chapter 2 - Literature Review
The literature review considered three main subject areas in order to assess the needs of the participants, the potential of an ARMaT device and the way in which it might be utilised:

Clinical - Basic anatomy and human movement is reviewed to provide performance data and design parameters for a new ARMaT device for the upper limb. The variety of clinical conditions that may benefit from such a device are presented to establish a potential user-base. The key issues associated with clinical conditions and how they affect the human body are reviewed to permit a non-specific approach to assessing sensorimotor learning and hence rehabilitation.

Engineering - Current research into rehabilitation is dominated by the fields of haptics (a system involving sensory feedback), rehabilitation robotics and how humans and machines may beneficially interact. The associated literature provides guidance for identifying and developing suitable ARMaT devices and their potential capabilities. Engineering measurement and assessment is reviewed in the context of supporting bio-engineering research in a predictable and reliable manner. Factors influencing the measurement of human performance, such as motivation and well-being, and how they might affect measurements are also identified.

Human-device Interaction - The processes and practice of physiotherapy and occupational therapy informed the design and limitations of any device used to support rehabilitation. Similarly, understanding the learning mechanisms that a therapist addresses informed how they might be considered and incorporated into an ARMaT device. The basic requirements and limitations that any real or virtual environment must address for beneficial interaction are

examined. The limitations of human senses and perception are examined to guide the development of any real or virtual environment that the ARMaT device will employ.

Chapter 3 - Methodology
Justification for developing a new ARMaT device is drawn from incidence and prevalence data for a number of clinical conditions and a variety of potential users.

A design-evaluate-redesign method is used to progress the project from the concepts contained in the main hypothesis towards a working prototype.

Potential movement parameters are examined for suitability as indicators of upper limb ability and pre-selected for assessment with the ARMaT device.

The reliance on measurement signals and digital processing and integration are discussed to establish the advantages and limitations of processing digital data to recover human movement parameters.

Reviews of statistical methods and statistical hypotheses are offered as they form the basis for developing and assessing viable movement parameters and any potential new metric.

Chapter 4 - Design Development
Technical and performance data is summarised from the literature review of rehabilitation processes and related haptic and robotic devices to guide the development and design of a number of devices leading to the working prototype.

Two concept devices are described which provided early development tools and a basic specification for all future devices. Concept A explored early haptic design and this informed the non-haptic device of concept B and also early assessments on normal participants.

The development and implementation of the non-haptic prototype 1 device and associated software is documented as this was used for the clinical trials which led to the first investigations towards establishing a new metric. The successes and limitations of prototype 1 are noted to support future device development.

An outline design for a future device (prototype 2) is documented as a development of prototype 1 that addresses the limitations and opportunities identified with prototype 1 and the results obtained.

Chapter 5 - Results
Experimental method is described for the assessment with prototype 1 and the related clinical assessment together with the statistical processes used to determine the new metric.

Results from both normal and patient participants using prototype 1 are presented as movement parameters developed from positional and temporal measurements. Parameters with the potential to describe upper limb ability and across all participants were extracted and examined.

A new metric is identified based on combinations of common movement parameters and this is correlated with clinical data.

Chapter 6 - Discussion
The new metric is compared with the two clinical scales and limitations of the work so far discussed to establish the potential of parameters and metrics to inform the model proposed in chapter1. Additional relationships within the movement parameters are reviewed for further examination and to inform future device development.

Chapter 7 - Conclusions and Further Work
The potential of a new ARMaT device and system is identified and further work noted. Development plans for prototype 2 are presented and further potential metrics are proposed.

1.3 Background

The main hypothesis for this thesis originated from early research into the potential for supporting the rehabilitation of children with cerebral palsy (CP). Whilst a great deal of attention is justifiably placed on stroke rehabilitation for an expanding and aging population, CP is a chronic condition with long-term demands on carers and health care provision especially as patients are living longer with improved health care.

Rehabilitation is commonly considered to be the effect of restoring something to a previous or normal state, and all living beings have the ability and innate desire to do this. This may not always be possible following severe injury or disease but degrees of rehabilitation are usually possible even if full function or independence is not achieved. In the context of acquired brain injury (ABI) such as may be experienced with CP, cardiovascular accident (CVA) or stroke, Parkinson's disease (PD) and traumatic brain injury (TBI), rehabilitation is a complex process of restoring or maintaining physical functionality whilst allowing and stimulating the brain to recover.

Whilst rehabilitation is a natural process, in health care the term is commonly used to describe medical interventions to support, guide or assist the body's natural ability to recover optimal function. Such interventions might include physiotherapy (PT), occupational therapy (OT) and speech therapy (ST) as well as surgery or the use of pharmaceuticals. Despite many years of successful treatment, there is still considerable debate whether a particular intervention is better than another and to what degree the body and brain will recover without assistance.

As many of the issues faced by CP patients are shared with other patients with an ABI, the scope of the project is potentially much broader than originally envisaged for the juvenile CP participant group. There is considerable commonality both within the direct effects manifested on the brain and body due to the different clinical conditions and in the resulting sensorimotor, physical and cognitive functionality. The processes whereby the patient recovers from an initial condition may vary in their detail but the external effects of the condition on a patient's abilities are often similar. These effects may include: change in muscle tone, loss of voluntary control and experiencing involuntary movements, bilateral variations in ability and reduced cognitive ability. There are usually identifiable stages of recovery which may include a plateau of recovery before progressing to a further stage and inevitably limits of recovery due to residual deficits. In all conditions, there is a spectrum of effects and potential rehabilitation scenarios which may depend upon the person, their age and environment, available care and access to medical facilities.

There are some notable advantages to working with children who are still learning many of the skills that adults may unfortunately lose following a stroke. Rehabilitation is a form of re-learning and this is potentially easier when the brain and sensorimotor control system (SCS) of the central nervous system (CNS) have not been fully developed to manage the many common and specialised skills needed for independent living. Children are known to have greater brain plasticity than adults (although some capacity exists into old age) and this plasticity offers the greatest potential for rehabilitation. Children are also generally open to new experiences and are usually willing to try activities without the preconceived ideas that adults might have as to the value of an exercise or therapy. In this sense children with CP

might be considered ideal neurological participants as they might help to identify the potential for rehabilitation from chronic and acute conditions.

There are inevitable disadvantages with a juvenile group as it is typically less homogenous than an adult group and cannot easily be motivated by adult requirements such as career and family/financial responsibilities. Children have not learned to rely on a complex activity such as driving which might direct their rehabilitation and, as children and patients, their sense of self-motivation might be limited. There are also physical issues in that a growing child with weakened limbs may require surgery to correct disparities in normal growth between the limbs.

The many complex processes of rehabilitation are not all understood in detail but the results can be measured against various scales of assessment for physical, sensorimotor and cognitive ability and other complex interactions. Most established measures of ability, and hence rehabilitation, are specific to a condition or treatment. Typically, they are bespoke measures developed in response to a particular need or aspiration rather than a general requirement to assess ability across a broad spectrum of subjects. In contrast, the main hypothesis of this thesis presumes that non-specific movement parameters exist which contain the characteristics required to codify simple or complex reaching tasks. Any suitable combination of these should therefore correlate with any other measurements of similar movement and such correlations are limited only by the specific and individual nature of the bespoke measures themselves. Hence, by measuring simple movements, a continuum of ability can be established that current measures can only capture within a limited and generally non-scalable range.

This project originated from a perceived need for an affordable, but sophisticated device which might facilitate the potential of rehabilitation robotics and haptic interfaces. This technology was identified as having the greatest potential for supporting rehabilitation from a wide range of conditions across varied age groups. Such a device would need to provide significant functionality and sensory-rich environments for users to benefit from three-dimensional (3-D) haptic therapy for the upper limb. To establish a specification for an affordable device all necessary design criteria were examined, including what measurements might be required to quantify ability. The unexpected absence of common and agreed quantitative assessments of upper limb rehabilitation re-directed the research and associated device development towards identifying a new metric of rehabilitation.

In developing the project, the author encountered many diverse opinions and proposed solutions to the problem of measuring state and progress in rehabilitation. These had developed over many years in response to needs, aspirations and advances in technology. In recent years, the availability of advanced mechatronic systems from engineering applications has facilitated complex measurements of movement including accurate position, force and acceleration in real-time. Each of these advances in otherwise proven technology offered great potential however, their inclusion and interactions with human abilities were not always assessed prior to implementation.

Most rehabilitation robotic devices were presented as supports to therapy, perhaps to minimise human or capital costs associated with medical care. As such they were used as a form of therapy or to deliver therapy by direct interaction with human participants. To mimic human movement, such devices needed to be very sophisticated and complex, responding

autonomously to varied movements. The control of such devices for safety and performance is the subject of continued research and development as the consequences of failure are potentially significant and undesirable.

The human body is a highly complex and variable mechanism with few universally agreed baselines of ability or performance spanning both normal and patient behaviours. Adding even more complex control and motivational systems had the potential to obscure the movements that define rehabilitation progress. To avoid such potential corruption the author proposed that simple measurements of movement with limited interaction was required to establish a method for measuring ability and hence rehabilitation. Parameters should exist for most normal movements and these could be extracted from basic positional and temporal data. If the measurements were reliable and believable then movement quality could be assessed reliably and reasonably accurately. If such results were repeatable and scaled to the individual, then progress could be measured reliably. Given these strong foundations, any measurement made with a simple system could be related to and used with more complex systems and methods of assessment.

1.4 Rehabilitation and Therapy

It was noted in section 1.3 that rehabilitation of the human body is a complex process which is difficult to quantify across varied subjects. Typically, it requires therapy - physical movement and interaction with the environment - to restore the complex capability that allows humans to thrive in a changing and uncertain world. Full recovery may not be possible and this must be determined on the basis of reliable assessments. Such assessments are primarily to gauge progress but they can also be used to judge the return on investment of time and resources or the efficacy of pharmaceuticals. Therefore, assessment of the effects of any therapy is fundamental to determining what is required next or if any further therapy is suitable.

A wide variety of studies and investigations have sought to identify the mechanisms underlying rehabilitation and therapies which support or promote it. These might be based upon established processes [1-3] combinations of therapy and assessment technology [4-8] or novel interactions with emerging technology [9-15]. Determining the efficacy of any therapy relies upon two critical elements. Firstly, there must be a desired outcome which can be identified, preferably one that supports the subject's activities of daily living (ADL). Secondly, a believable and reliable measuring system is needed to assess progress and to provide valuable feedback to subjects, carers, therapists and clinicians. Ideally, the system should allow assessment of initial ability, determine quantifiable progress, or lack thereof, and suggest where therapy has been effective or where further therapy might be needed. With sufficient background data, such a system would be able to correlate performance within and between subjects and/or therapies and/or other medical interventions. Such a system could also be used to assess learning progress and skill retention.

In the context of upper limb rehabilitation, therapies exist to support or treat chronic conditions such as CVA or stroke, CP, TBI or other conditions in major subject groups [16-18]. Typically, such conditions extend or develop over many years and subjects may not recover full functionality. Similarly, treatments exist for acute conditions such as sports or work injuries which often result in full recovery. The efficacy of these therapies is often difficult to determine and some assessments are subject to highly variable inter-rater and intra-rater results at different stages of recovery. These issues are significant for chronic conditions where repeated therapy is often required.

The motivation for this project came from a generally held view that patients with many clinical conditions can, and do, benefit from PT, OT and ST, and possibly the combined use of all three. The widespread use of such therapies indicates that they are generally beneficial although the degree to which they actually enhance natural rehabilitation processes has not been fully determined. The apparent shortage and/or availability of these skilled therapists may have resulted in potentially less than optimum recovery for some patients [19].

There is a wide range of conditions which are currently treated with a combination of pharmaceutical drugs and physical therapies. Some of these treatments can only provide relief from pain or discomfort, such as arthritis. Others can assist the permanent, if partial, recovery of the sufferer following an ABI in children, for example, providing near full recovery in extreme cases. In all cases, there is little dispute that therapy has beneficial effects although the lack of consistency in present measuring systems precludes definitive cross-comparison of treatment regimes [20]. Therapy is typically beneficial and no harmful effects have been

noted by the author in the literature review. There does not appear to be any problem with the therapy received, rather that not enough therapy is provided due to limited resources.

Many of the exercises or procedures that a physiotherapist provides are simple in form, repetitive in nature and are generally extendable. That is, the same form of exercise can be made more challenging to the patient both physically and mentally. Long-term benefits rely on continued repetition within the exercise regimes set by the therapists with regular feedback on progress [21]. Without the therapist to guide and encourage the patient and/or their carers, this long-term benefit may not be realised and initial progress may be lost altogether [22]. As machines can conduct repetitive actions efficiently, robots would appear to be an ideal supplement for mass PT. The use of robot mediated therapy is generally based upon the delivery of known, controlled exercise which may be repeated with little involvement from the therapist [23, 24].

If the benefits of long term PT are accepted, but the human resources to carry it out are limited, then there exists an opportunity for automatic devices to be used to support PT and possibly OT and ST. Such devices will inevitably present a cost to health care providers and/or patients. In order to promote any additional automated PT regimes, clear benefits to the patient and/or the health care provider need to be demonstrated.

In the context of treatments related to this project, PT may be described as *"the use of physical manipulation of active or inactive limbs to promote recovery of function and control".* How this is done is sometimes quite obvious. For example, following a simple fracture, a physiotherapist might help a patient to exercise the limb to maintain previous mobility and flexibility, whilst supporting the injured area as it heals. Such activity prevents the muscles becoming weak, limits the formation of scar tissue and limits the shortening in ligaments. When the primary injury has healed, the patient can then resume their activities, generally with no permanent loss of function. At the other extreme, a child with an ABI in the areas affecting motion may lose all muscle control in their limbs without any physical injury to the affected limb. The effect may be instantaneous or progressive. Here, one of the therapist's objectives is to maintain limb function whilst the brain heals. The more subtle effect might be to re-train the brain to regain function so that the limbs can be operated by the child independently. This is an emerging field of rehabilitation typically described as neuro-physiotherapy (NPT). The mechanisms for this are not well understood, but the effects can be dramatic, with significant spontaneous recovery of limb function and control.

In the treatment of stroke patients, typically affecting the older generation, similar PT processes are used to those for children although less dramatic results are evident due to the potentially reduced plasticity of the adult brain. More likely, is the learned misuse that an adult develops following a stroke in order that they may compensate for the residual disability [25]. This self-learned behaviour is often sub-optimal but uses up the residual and/or compensating neural pathways. It becomes a new map or paradigm for a required ADL even if the subject knows that it is a poor substitute for previous function. In essence, they are coping, maintaining their dignity and that is better than not being able to care for themselves.

Therapists form a relationship with their patients and offer encouragement and support as well as valuable exercises. This is very important to the patient and must not be ignored in any automated therapy environment. In many ways the relationship and attitude of patients and PT/OT/ST staff may influence the outcomes as much as the treatment itself [26]. Hence, it is

important to communicate and demonstrate progress and the measurable benefits of any treatment.

Many well-received assessment procedures or methodologies exist which provide qualitative data without elaborate equipment [27]. Basic statistical correlation between systems is often good but lengthy assessment processes normally preclude multiple contemporaneous assessments [28]. As a result, data sets may suffer from lack of continuity for patients and ultimately for patient groups. To overcome some of these limitations, rehabilitation robotics and related technologies [13, 14, 29, 30] have been used to deliver therapies and assessment for upper and lower limb function. These therapies can be usefully described as automated rehabilitation therapy (ART) and this generic term is proposed and adopted in this thesis. Typically, these systems were devised to emulate PT and were not expected to improve upon it. However, Burgar [29] notes that ART systems actually resulted in better outcomes than conventional therapy in upper limb assessments. These systems can provide quantitative measures of human performance that can be compared quickly and meaningfully with data obtained from previous treatments and other similar measuring systems. This allows clear evidence of measurable progress that can be communicated to the patient and carers, and shared between clinical staff.

Unfortunately, robotic systems suffer from their own limitations. Firstly, the data produced is not readily interchangeable with established qualitative assessments, which currently dominate rehabilitation practices. Secondly, the costs and safety procedures associated with the use of robotics currently limit widespread use and consequently mass data capture and analysis. Attempts have been made to bring simple automated rehabilitation and/or measurement systems within the reach of everyone and these are discussed in detail in chapter 2. However, whilst the benefits are rarely disputed these existing systems have not gained widespread acceptance and use and assessments are not readily converted. A simple, affordable and reliable assessment system is still required.

1.5 Visualising the Hypothesis

In order to explore the main hypothesis, a simple but extendable model of human ability was required. This was developed by the author and one of many potential visualisations is shown in Figure 1-1 and is further developed in this section. It is referred to again in chapter 6 where the relevance to clinical assessments is presented. This model could be used for any body segment or system but here is applied to the upper limb and specific CP related assessments.

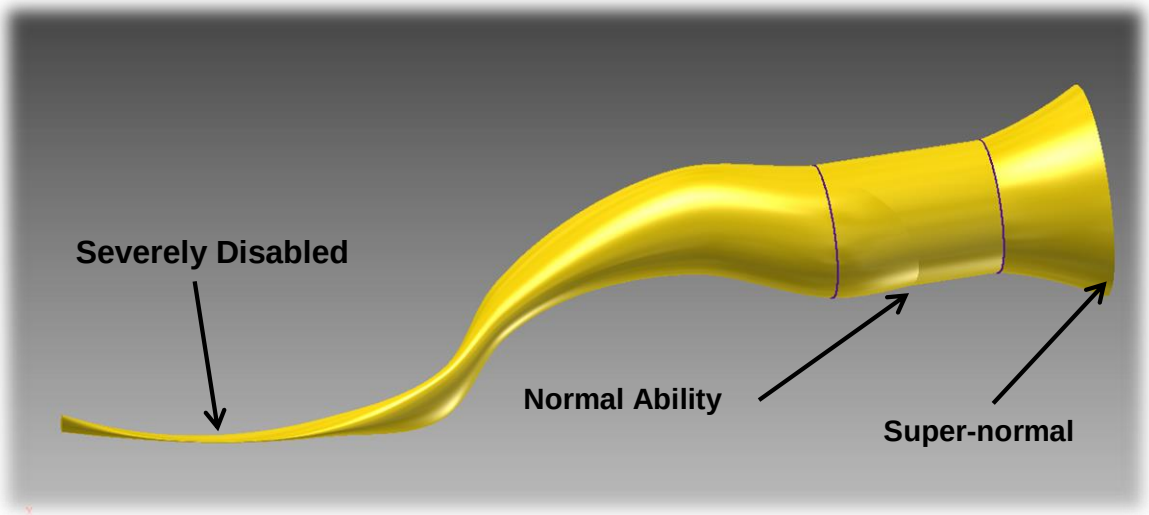


Figure 1-1 Continuum of Ability

A complete version of any model of ability may well contain more than three dimensions but the model in Figure 1-1 is depicted as a 3-D image for simplicity. It describes a continuum of ability which spans a wide range of abilities from severely disabled to super-normal. Such a continuum is obvious given the range of abilities, and changes in those abilities, that humans demonstrate.

The continuum represents abilities that require cognition, planning and physical execution in real time rather than thought processes alone; these being minimum requirements for the rehabilitation of daily abilities. Typically normal behaviour (ADLs, catching a ball, cycling, dancing) is represented by a large and balanced circular region which extends for some distance with only small changes, reflecting the typical abilities that most people could attain and sustain. The diameter of the continuum here represents potential capacity or ability as it is not limited by uncontrolled conditions such an injury or illness. This region might be used to assess typical healthy ability and as the basis for engineering design of products such as cars. A region is shown beyond normal which might be termed super-normal, applying to athletes and specialist coordination activities (piloting an aircraft, advanced crafts, playing a musical instrument) that most people could not attain or could not sustain for prolonged periods.

The largest part of Figure 1-1 is shown as an irregular tube that is reducing in size (capacity) and is highly variable in section and orientation. This represents a large spectrum of disability that extends to an extreme of no volitional control that might be representative of a severely disabled person requiring constant care and support. At this extreme it may not be possible to expect any sustained rehabilitation although this should not be ruled out. This thesis addresses

the majority of the continuum where full or partial rehabilitation is possible and may benefit from a new ARMaT device.

The continuum might be defined by many individual abilities which could be considered as strands running through the continuum. Three major strands have been considered as a selection of the potentially large number of strands that are needed to define ability and to explain responses to external and internal stimuli. These three strands are shown in Figure 1-2 and described below. Each of these may potentially occupy a multi-dimensional space, which could be measured directly or implied from other measurements:

- Physical – the ability of the body or segment to perform voluntary movements with sufficient force to achieve a task
- Cognitive – the ability to interpret need, data, action and interaction with an environment
- Sensorimotor – the ability to detect, translate, monitor and control a desired action into suitable movement.

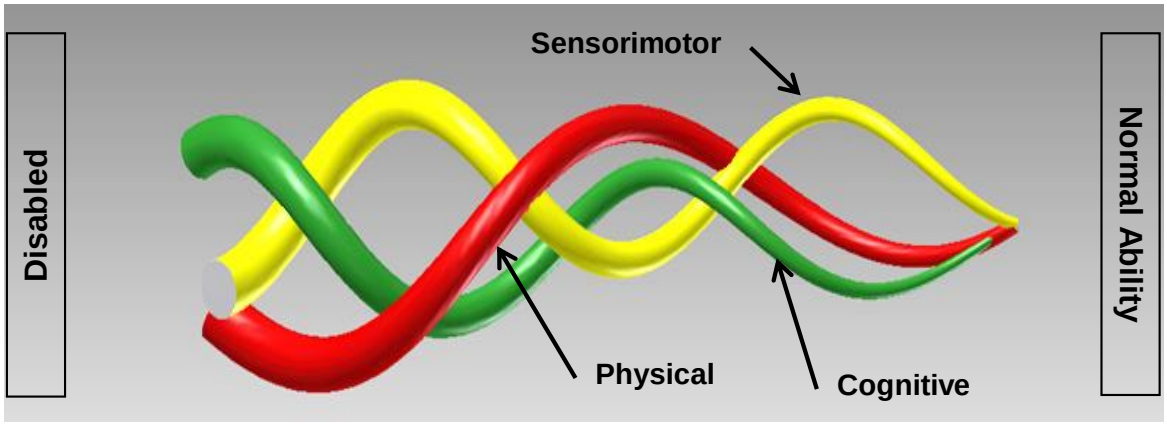


Figure 1-2 Ability Strands within the Continuum of Ability

In Figure 1-2 the strands are continuous in section shape but variable in diameter, orientation and length, crossing and perhaps intersecting with other strands. Normal ability is represented by the thinnest part of the strand bundle to the right where the various abilities are refined and aligned. Here potential capacity and ability are not restricted by innate ability, rather by opportunity or motivation. People with aligned normal ability strands have the capacity to do most things but might chose not to. The previously noted "super-normal" strand bundle is not shown but would be a set of even more refined ability strands. Again, the dominant region to the left of Figure 1-2 represents the highly variable nature of abilities in people with conditions that affect one or more ability strands. This region is represented by highly diverging strands and the interactions between them, some of which may be undesirable. As basic ability diminishes, the strands become more chaotic or may disappear altogether. This research did not directly address this extreme but may help inform other work which does.

The measurements required to assess ability within each of these strands could be complex or simple. The most reliable engineering measurement is movement or simple displacement, which addresses all three strands either directly or indirectly. As controlled movement in

response to a stimulus depends upon some ability within all strands, simple movement should reflect all three abilities. Whilst these abilities are probably the dominant strands to consider, others such as motivation and environment are also valid and could be added to this general model as noted in section 2.5.3. The question of suitable measurands to capture these other strands is not addressed in this research project although tools do exist for this pupose.

It is important to note that this model is not expected to be linear, nor are the dominant strands implicitly mutually dependent along the length of the continuum for every type of movement. For upper limb reaching tasks, they are however, unlikely to be independent or discontinuous. The strands are shown as changing in multi-dimensional space to indicate that ability or changes in ability in one strand might be disproportionate to that in another strand at a given point in time or stage of rehabilitation or development.

1.5.1 Measuring Ability during Rehabilitation

In Figure 1-1, the broad span indicated from severely disabled up to normal is intended to describe the wide range of partial abilities that are not usually seen in normal development. Normal ability is explored in more detail in section 2.3 but can be visualised as a relatively narrow and predictable state compared with that associated with clinically significant impairments. Improving ability along the normal section of the continuum might be considered a natural process during normal development with eventual, but predictable, decline as the human body ages or suffers minor injuries. Increased effort, motivation and opportunity has the potential to enhance some abilities in most people, such as athletes or soldiers, so these might be dominant factors in moving from normal to super-normal. Such improvement should be measurable on this continuum and may distort the strands locally as one ability is honed at the cost of another.

The sudden loss of acquired and/or developed ability and/or function does not represent a typical state of progress and may result in permanent loss of ability and function. Significant impairment in any strand is normally reflected in others such as loss of sensorimotor capacity impacting on reaching tasks despite there being no physical damage to the upper limb. Typically, most established upper limb rehabilitation measures span a limited range from a degree of disability to near-normal ability, such as being able to manage ADLs unaided. Similarly, specific sports will have bespoke and general measures of ability such as temporal measures for running or general aerobic fitness. Extreme ability in specific tasks might be considered super-normal where the refinement and alignment of abilities is optimised to a task. Olympic athletes might be among this unusual group.

The spectra of abilities for significant medical conditions are extremely difficult to map, given the wide variety of both subjects and symptoms. An indicative spectrum of ability is suggested in Figure 1-3 for CP, superimposed upon the continuum. The shape of this spectrum is intended to indicate that the edges defining CP, and hence measured ability within it, are not easily defined or codified. Other typical spectra could be shown for conditions such as PD, perhaps overlapping with that for CP. Abilities resulting from head injuries might be too diverse to represent as a simple spectrum and might be better described by a variegated cloud covering a large section of the continuum. It is clear from this analogy that defining the applicability of any assessment and any potential overlap with another related or unrelated assessment is not simple.

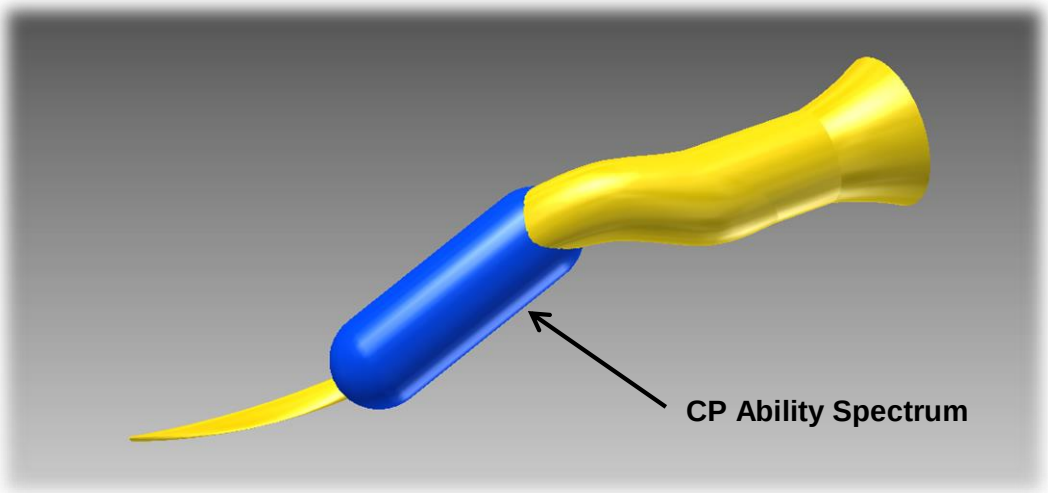


Figure 1-3 Continuum with Superimposed CP Ability Spectrum

To identify ability, and hence changes in ability, along the continuum requires a measurand which must be able to discriminate between states and must provide quantifiable results based upon reliable measurements. Typically these might be kinematic measures (time, displacement, velocity, acceleration) based upon meaningful movements that represent some degree of challenge to a subject. Such measures are rarely used in isolation. Rather a compound measure of achievement or outcome measure is often used, such as reaching a number of targets in a given time, as in the nine hole peg test (NHPT) [31].

Ideally, the kinematic measurements themselves would be sufficient to provide adequate discrimination of ability as these can be scaled and transferred readily. However, it is more likely that movement parameters that combine such simple measurements would be more meaningful. Such parameters might have the potential to describe ability across a large portion of the continuum or they might be limited to specific regions. Movement parameters might have standard units or they might be collective measures that can be combined geometrically. Each parameter might describe a particular characteristic of a movement such as accuracy or efficiency or they may be related to other as yet undefined movement qualities or characteristics.

With multiple parameters being readily derived from simple movements (as described in section 3.3) there may be a number of parameters that measure similar characteristics. By rationalising potential movement parameters into principal characteristics the most influential or representative parameters for any characteristic might be identified. These principal characteristics, when combined appropriately, could describe the size and orientation of an ability strand. This arrangement is suggested in Figure 1-4 where the sensorimotor strand from the normal end of Figure 1-2 is defined by three principal movement characteristics – accuracy, efficiency and quality.

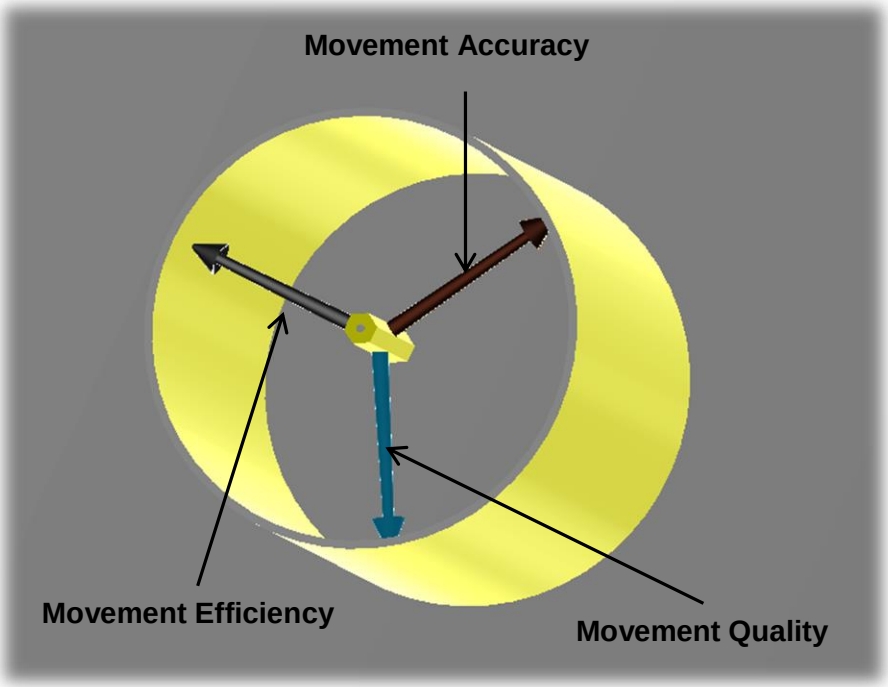


Figure 1-4 Normal Sensorimotor Ability Strand with Principal Characteristcs

The normal portion of the strand contains balanced characteristics shown by the arrows being of equal length and originating at the centre of a circular strand section. For comparison, a section of the same sensorimotor strand within the disabled region of the continuum is suggested in Figure 1-5. Here the characteristics are unbalanced and may originate to one side of the strand's centreline. The characteristics are equally valid in making an assessment of ability but their size and distribution will change with rehabilitation progress.

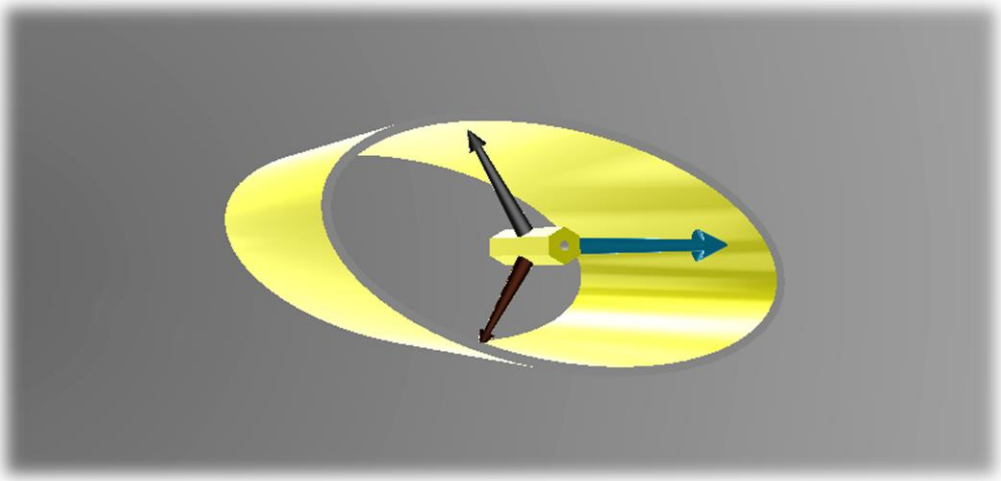


Figure 1-6 Patient Sensorimotor Ability Strand with Principal Characteristics

As noted earlier, the individual movement characteristics might be represented by any number of parameters. This is indicated in Figure 1-6 where part of the potential characteristic "movement quality" arrow from Figure 1-4 is shown. The size and weight of this arrow can be identified from related but potentially orthogonal movement parameters such as time, displacement and speed. Additional potential movement parameters for simple reaching tasks are introduced in section 3.3. It is desirable, and computationally efficient, to reduce the number of parameters to a minimum that captures the movement characteristic.

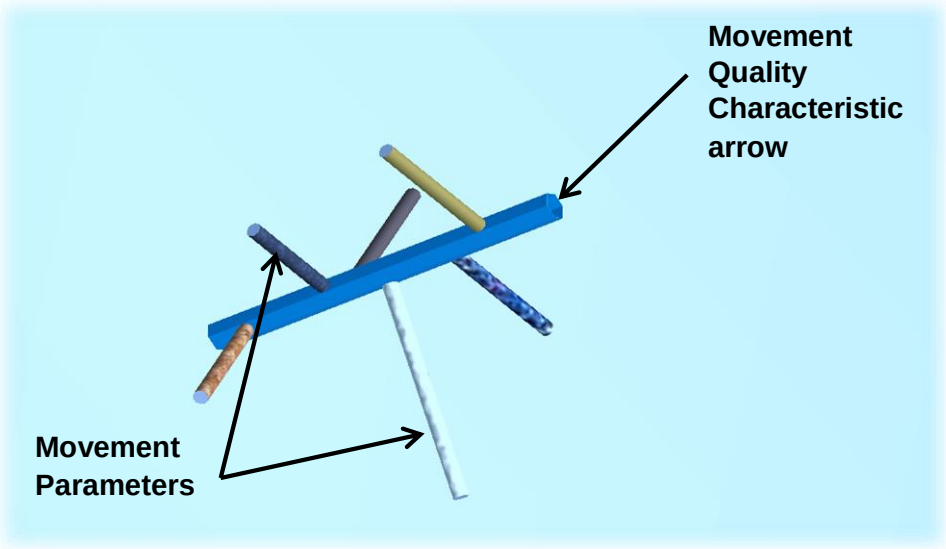


Figure 1-5 Movement Quality Characteristic formed by Movement Parameters

Combining simple movement parameters into principal movement characteristics permits ability strands to be identified and correlated with established clinical assessments. Having established a pattern of measurement, these ability strands can be combined to describe a point or region within the continuum of ability and hence record progress within the continuum. Developing a novel metric which brings the above processes together is the aim of this thesis.

1.5.2 Clinical Assessments of Ability

The image in Figure 1-7 shows a view of the ability strands taken from the region for CP noted in Figure 1-3. Two relevant CP assessment scales are overlaid, representing different measures of abilities and how they might intersect the ability strands, and each other. Their shape and shading indicate likely limits of assessment within the CP spectrum. These two assessments scales are described in detail in section 5.1 but it is appropriate to note here that one is specific to children with CP whereas the other has been used on a wide range of clinical assessments.

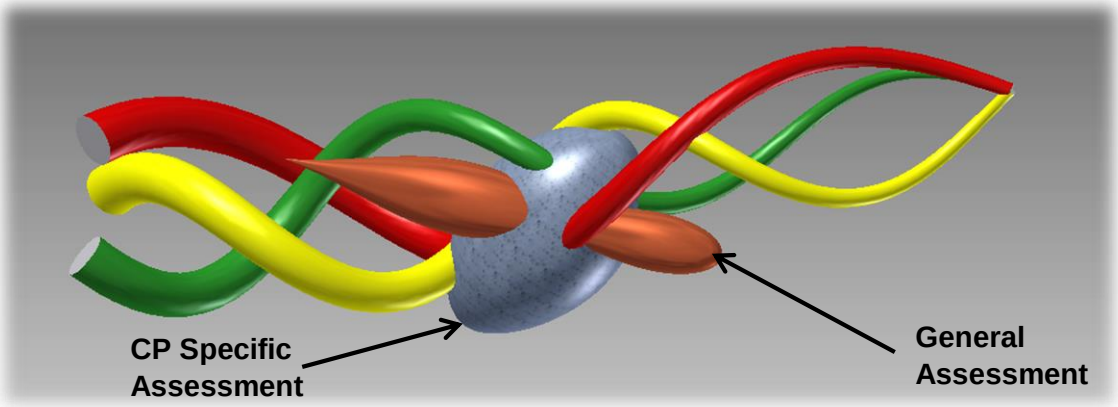


Figure 1-7 Clinical Scales Superimposed on Ability Strands

The intention of the graphic in Figure 1-7 is to indicate that different measures do not necessarily assess similar abilities even within the same subject or group. Two scales which correlate well may actually be almost orthogonal to each other within any one strand. Similarly, the emphasis on the three main ability strands of a scale within a rich environment may be quite different to another scale used within a simple environment. Hence, the most reliable portion of the scales may not coincide in any plane. It is common practice to use statistical relationships between established scales to compare therapies with so-called gold standards, none of which have truly quantifiable scales. It is therefore possible that poor correlations may be a result of inappropriate measurements rather than dissimilar benefits between therapies. Conversely, whilst good correlations may indeed indicate similar benefits, there is the potential for misreading such results outside of a very limited range.

It is likely that similarity and underlying correlations between assessments is contained within the simplest elements used in the assessment – simple movements which can be described in one, two or three-dimensions. The simple model described in Figure 1-1 has the potential to describe development over time and in response to varied types of intervention such as training, therapy or pharmaceuticals. If calibrated (in whole or part), it could also describe rehabilitation of any appropriate body segment or system which might be described by simple movement measurements. The model can therefore, be used to test and elaborate upon the hypothesis posed in this thesis.

1.6 The Potential of a New Metric

The literature shows that extremely elaborate devices and systems have been, and continue to be, developed to support rehabilitation. Some devices, such as the InMotion™ ARM are already being deployed into hospitals [11, 15] and may become familiar equipment in many clinical environments. They will, presumably, continue to evolve, becoming more affordable, and more accessible and may provide the support and/or therapy that is in such great demand. Interestingly, the initial concerns regarding suitable measurands identified by the author in section 1.3 remain largely unresolved. Despite significant progress towards this goal [32], no standardised and scalable form of ability measurement has been established for the upper limb.

There is a noticeable trend away from expensive and elaborate bespoke haptic robotic solutions towards smaller scale, and more accessible systems of therapy and measurement that can provide reliable assessments that correlate well with other clinical scales [32]. The following points are summarised from the literature as being the most significant development criteria for the next generation of ART devices:

- More therapy, and possibly more variety, is better
- Access to affordable therapy is important
- Variable frequency and duration of therapy could yield cost benefits
- Therapy may be required for a large portion of a patient's life
- Patients need to engage with the therapy
- Patients and carers need feedback and support for any therapy
- Elaborate or restrictive measurements are not favoured
- Patient directed therapy is valuable
- Home-based therapies are valuable
- Cognitive training is valuable
- Mental state and environment can affect results
- Holistic approaches may yield better results.

These concepts are becoming more established as research in this area develops and they have guided the development of the concept designs and prototypes noted in this thesis.

This thesis attempts to address the requirements of health care practitioners and the needs of their patients by using established and innovative engineering solutions. This bio-engineering approach is a largely undefined and rapidly emerging field of research and development. It continues to expand as more challenges are accepted by engineers and clinicians, working together to support and treat established and new medical conditions. By applying engineering concepts and design solutions to medical problems more reliable results can be predicted and obtained. Advances in the use of materials and equipment continue to allow improvements in diagnosis and treatment and this pattern of development continues to expand.

Biomechanics, a particular aspect of bio-engineering, is the measurement of both complex and simple human behaviour, both in healthy subjects and in those affected by known medical conditions. Similarly, the interaction of subjects with new environments and technology

provides fertile ground for needed research to improve understanding so that new and improved treatments can be developed. Where a condition affects the normal functioning of a physical or neurological system, measurements against known normal capability are essential in assessing the effect of any intervention. To be valuable such measurements must be reliable and repeatable as well as meaningful when compared with established scales.

Simple measurements have the benefit of being readily understood and they are typically more reliable and repeatable than complex or multi-facetted assessments. The measurement of movement is essential to assess the effect of a condition or intervention in upper and lower limbs, these being the most mobile body segments and those that significantly affect activities of daily living.

To simplify understanding of the multitude of systems in use or under development the author proposes the ARMaT classification for the device developed within the project. Whilst the primary intention is measurement, any appropriate exercise is also therapeutic. Hence, the device will probably provide both functions and should not be limited to one nor should possible therapeutic effects be ignored.

1.7 Chapter Summary

Knowing that a diverse range of beneficial therapies is available is encouraging to a wide range of patients and carers who need help, support and encouragement following illness. However, a simple, quick and cost-effective method of assessing rehabilitation progress remains elusive. What is needed is a simple "ruler" or metric that almost anyone can use to quickly measure and assess progress relative to their own state of rehabilitation. To maximise longitudinal benefits, such a metric must be developed from a traceable and reliable assessment that reflects a wide continuum of ability.

Is it possible to use such a basic "ruler" to assess progress in such a complicated mechanism as the human body? Provided that progress is relative to a user's ability and not to an arbitrary scale then this should be possible. If the metric is scalable and can be applied quickly enough to permit repeated and non-invasive measurements then the results should be valuable. The measuring device is not itself a therapy although the act of measurement will necessarily appear as a sort of exercise and may well be beneficial. For this reason the device was defined as ARMaT rather than ART.

Whilst this project was originally conceived as applying to the rehabilitation of juvenile CP patients, the methodologies and equipment used can find applications for a variety of conditions. Stroke rehabilitation, support for those with Parkinson's disease, sports and work injury rehabilitation and, potentially, mental health issues are all valid areas of work and research. These areas have been drawn upon to inform suitable devices, environments, interfaces and experimental procedures. Hence, the outcomes of the present research and development may well be applicable to a wide variety of conditions and treatments that currently benefit from physiotherapy.

The prototype developed and tested addressed the requirements for a simple device that allows reliable measurements of ability and progress in simple reaching tasks throughout a rehabilitation process. Other therapies and assessment systems are available and continue to develop to meet additional rehabilitation needs but reliable, quantifiable and rapid real-time measurement systems are still not available.

1.8 Glossary of Terms

There a number of acronyms specifically created to describe the parameters and new metric. These are introduced with the text but are noted here for reference. The terms noted in the following tables have been used for consistency and clarity throughout this text. To avoid confusion where published texts have been referenced the following definitions have been applied in the context of the whole paper rather than selectively.

1.8.1 Parameter Acronyms

Acronym	**Meaning**
ALHS	Area enclosed by path to left of ideal trajectory
ARHS	Area enclosed by path to right of ideal trajectory
BS	Bulk speed = path length / path time
DA	Displacement area bounded by path and ideal trajectory
IT	Ideal trajectory
LIT	Length of ideal trajectory
MaxYDisp,	Maximum y displacement
MaxX	Maximum x displacement
MinYDisp,	Minimum y displacement
MinX	Minimum x displacement
NA	Net area (ARHS-ALHS)
MPD	Maximum path displacement from ideal trajectory
PL	Path length
PMPD	Position of maximum path displacement along ideal trajectory
PT	Path time
TDA	Total displacement area

1.8.2 General

Term	Description
ARMaT	Automated rehabilitation measurement and therapy. Classification for this research device.
ART	Automated rehabilitation therapy. Includes: rehabilitation robotics, haptics, etc.
Body segment	A component of the body used for movement or activity; the forearm is one segment of the whole arm and shoulder.
Exteroceptive Sensors	Typically these would be touch, temperature, sound, etc.
Normal	Individual without a specific condition (which might affect results) who uses a device/system as an able-bodied reference for a healthy trial.
Participant	A normal or healthy individual who participates in a research study
Patient	Individual with a relevant clinically assessed condition who uses a device/system therapeutically.
Proprioceptive sensors	These internal sensors sense any one or all of the following in a segment joint: position, orientation speed.
Subject	Normal or patient individual not associated with a research study
Upper Limb	The arm from the shoulder joint to the fingers. The hand is not specifically assessed but basic grip ability is required.
User	Individual using the device with or without a specific clinical condition.

1.8.3 Medical

Term	Description
Ataxia	Loss of order; problems with movement, balance and speech.
ABI	Acquired brain injury; injury acquired after birth.
ADL	Activity of daily living – often used as a set of objectives in rehabilitation therapy – may include brushing hair, toileting, etc.
Acuity	Keenness or clarity of a sense.
Anton's syndrome	A form of cortical blindness in which the patient denies the visual impairment. Caused by damage to the occipital lobe.
Aetiology	Study of the causes of conditions.
Audio acuity	Ability to hear and discern sounds; clarity of hearing
Astigmatic	Caused by changes in spherical radius of cornea – produces distorted and/or blurred vision.
CNS	Central nervous system.
Cosmesis	Surgical or therapy intervention for cosmetic reasons.
CP	Cerebral Palsy – either from birth or following disease – dystonic/athetoid, spastic and ataxic.
Emmetropic	In the right measure or size – vision will be normal.
Friedrich's Ataxia	A progressive neurodegenerative disorder; typical onset 2-16; weakness and loss of vibration and joint position senses; also affects the heart.

Term	Description
fMRI	Functional magnetic resonance imaging.
Geriatric	Normally considered as aged over 65.
Hemiplegia	Full or partial paralysis of one side of the body due to disease, trauma or stroke.
Hemispherectomy	Surgical removal of a cerebral hemisphere (as to control severe epileptic seizures).
Hyperopic	Long-sighted – the image is formed behind the retina.
Incidence	Number of occurrences or recorded data of a condition or event in a fixed period. Can be based on percentage population or actual quantities.
MA2	Melbourne assessment 2. One of the clinical scales used with patient participants; an updated version of MUUL.
MUUL	Melbourne unilateral upper limb assessment. One of the clinical scales used with patient participants.
Monosynaptic	Direct neural connection.
MEP	*Motor-evoked potential; used in conjunction with TMS.*
Myelination	Process during which neurons and dendrites become coated with a fatty substance (myelin) to enable neural impulses to travel faster.
Myopia	Near-sightedness. Focusing defect in which the eye is overpowered.
Myopic	Near-sighted – the image is formed in front of the retina.
NPT	Neurophysiotherapy; physiotherapy targeted at rehabilitation following injury to the brain and/or CNS.
Nystagmus	Involuntary rapid movement of the eyes in the horizontal, vertical or rotary planes of the eyeball.
OT	Occupational therapy.
Paediatric	Aged from birth to 16 years; target CP group for this research.
Parkinson's Disease (PD)	A progressive neurological condition; insufficient dopamine results in slowness, tremor, rigidity.
PT	Physiotherapy.
PET	Positron emission tomography
Presbyopic	Old sight: limited near-point focus – the closest distance at which a person can focus increases with age.
Prevalence	The residual occurrences of a condition or event following; typically survivors of a life-threatening illness or those with residual injury or impairment.
Proprioceptive feedback	Information from joints muscles and skin which is used be used to plan and execute movement.
PT	Physiotherapy.
SCS	Sensorimotor control system.
Sensorimotor function impairment	Any impairment in the sensing or actuating systems in the subject's body. This includes visuomotor impairment.
Supraspinal	Located above the spine.
Snellen test	Dutch ophthalmologist who introduced the Snellen chart to study visual acuity.

Term	Description
Spastic diplegia	CP characterised by muscle stiffness in extremities.
Squint	Partly closed eyes; “lazy eye”.
ST	Speech therapy.
Visual Acuity	Commonly 20/20 (6/6) denoting an average ability to read small characters at fixed distances such as the Snellen test; degrades with age.
TBI	Traumatic brain injury – following accident, disease or surgery and resulting in loss of brain function.
Tone	Muscle tone or stiffness described as either hyper or hypotonia
TMS	Transcranial magnetic stimulation used to stimulate area of the brain, typically sensorimotor centres.
TPT	Tyneside peg test. The clinical assessment used on all participants which forms the basis for comparison with new measurands.

1.8.4 Engineering

Term	Description
Active mode	Patient-active mode is used in varying degrees to challenge a patient’s ability to carry out a range of motions.
Accuracy	Closeness of a measurement to a known standard.
ADC	Analogue to digital conversion – process of translating analogue sensor data to digitised data for use in computers, etc.
Admittance control	Control system which registers user initiated force input and responds with a displacement that limits movement to represent the required environment.
Ballistic movement	Initiated by rapid muscle contraction and generally coarse in trajectory and typically followed by a fine motor movement in actions such as catching a ball.
Control strategy	A sequence of actions to effect a desired outcome. In human movement this often combines ballistic and fine movements
Control System	Electrical, electronic, computer or mechanical interface to provide safe and effective control of the mechanism to meet operational parameters.
Differential feedback	The rate of change in error sensed between the desired path and the actual path is amplified and used to correct the next control signal.
Drive	Components required to actuate a mechanism; may include electric motors, pneumatics, hydraulics, linear or rotary actuators together with any necessary motive power supplies and amplifiers.
Elastic	Strain is proportional to applied load. Stress and strain are in phase.
Force Transducer	Device to measure the forces exerted by the user, patient or mechanism in both passive, active or active passive mode.
Haptic	From the Greek word haptein, to grasp although generally applied to sensory interfaces with mechatronic systems.

Term	Description
Impedance control	Control system which registers user initiated movement and responds with a force that limits movement
Inverse kinematics	The process of determining the movement of interconnected segments of a body or model.
Kinematics	The branch of mechanics concerned with motion without reference to force or mass.
Magnetorheological fluids	A fluid which changes its viscosity/stiffness when a magnetic field is applied.
Measured Data	Data recorded during experimentation; either manual records or automated data recording.
Mechanism	Mechanical components or assembly used to impart forces and/or motion.
Mechanical singularity	An uncontrolled direction of motion; poses inherent control and hence reliability and safety issues.
Mechatronics	Technology combining electronics and mechanical engineering
Noise	Unwanted signals that interrupt or mask true sensor inputs or control outputs commonly found in electromechanical systems and neuro-simulation models.
OS	Operating system for a computer
Passive mode	Used to guide a subject through a set of exercises; subject experiences a range of motions precluded by their condition
Passive-active mode	Subject can initiate various motions but may not be able to complete them satisfactorily so the ART provides varying amounts of support and/or guidance.
PC	Personal computer – desktop or laptop using an operating system such as Windows™ or Linux™.
PIC	Programmable integrated circuit. A single chip controller which can be programmed to accept a variety of inputs, process them in real-time and provide useful outputs.
Pre-processing	Modifying data to convert it for digital transmission or filtering noise.
Precision	Repeatability of a measurement.
Post-processing	Modifying data to extract useful components or combinations of data streams.
Proportional feedback	The error sensed between the desired path and the actual path is amplified and used to correct the next control signal
Raw data	Data captured from sensors without filters or modification from original structure.
Resolution	The smallest identifiable component of a measurement.
Universal Serial Bus (USB)	Standard, cross-platform, data exchange protocol permitting high data transfer rates between peripherals and PC.
Virtual Reality Environment (VRE)	A computer generated environment which permits and/or encourages the user and patient to perceive environments other than the device/room in which the experiments are undertaken.
Visco-elastic	Extension is related to applied forces and rate of strain. Stress and strain are not in phase.

1.8.5 Statistical

Term	Description
Average	Typically interpreted as the mean of a data set.
Autocorrelation	Inherent correlation between two variables.
Bayesian inference	Using Bayes rule to update the probability estimate for a hypothesis as additional evidence is acquired.
Correlation	Association between two sets of data.
Covariance	Measure of how much two variables vary together.
Dependent Variable (DV)	The factor investigated using the null hypothesis. If alternative hypothesis is correct the DV will depend on the IV or IVs.
Independent Variable (IV)	The factor that is varied to examine any effects on the DV
IRA	Initial regression analysis: used to determine dominant parameters.
Kurtosis	A measure of the shape of frequency distributions.
Mean	Arithmetic average of all results.
Median	Middle value (or average of two adjacent values) in an ordered array; unaffected by extreme values.
Mode	Value which occurs most frequently; bimodal data suggest non-homogeneous sampling.
Normal distribution	Naturally occurring distribution of measured data against frequency.
Nominal Data	Non-parametric data obtained from survey without known interval relationships
Non-parametric	A population or application without known distribution.
Ordinal Data	Non-parametric data used to ranked results without known intervals.
Parametric	A population having a known distribution.
Pearson correlation coefficient	A measure of correlation for scale data; both variables must have a normal distribution.
Percentage	Proportion times 100.
Principal Component Analysis (PCA)	Process to identify a reduced set of underlying superordinate dimensions from a larger set of measured linearly combined variables which describe the maximum variance.
Proportion	Comparison of one component with whole population.
Quantitative data	Numeric data from physical measurements – typically interval scale data.
Qualitative data	Records of counts, instances or non-numeric events – typically nominal data or ordinal scale data.
Range	Difference between highest and lowest data values.
Rate	Instances in a period divided by total in a given time. Typically used for incidence and prevalence of conditions.
Ratio	Comparison of two counts.
Scale Data	Parametric data based upon a predictable and relevant scale.
Skewness	Measure of non-symmetry of frequency distributions about the mean.

Term	Description
Spearman Ranked Correlation Coefficient (Rs)	A measure of correlation for nominal or ordinal data; range = -1 to +1. Not as sensitive as Pearson's coefficient. Can be used when only ranks are available.
Standard deviation	Measure of variation: a line drawn from the mean value to a point of inflection on a normal distribution curve.
Standard Error	Standard error of the Mean: standard deviation divided by the square root of the sample size.
Variation	Spread of a distribution curve.

1.9 Nomenclature

1.9.1 Statistics

Notation	Definition
N	Number of results
$\sum X$	Arithmetic sum of population variable X
$\overline{X}$	Mean of all population values = $\sum X / N$
$\sum(X^2)$	Sum of squares of variable X
$(X - \overline{X})$	Deviation from mean
$\sum(X - \overline{X})$	Sum of deviations from mean; always equals zero
s^2 - sample σ^2 - population	Variance = $\frac{\sum(X - \overline{X})^2}{(N-1)}$
	Variance = $\frac{\sum(X^2) - (\sum X)^2 / N}{(N-1)}$
s – sample σ - population	Standard deviation = $\sqrt{s^2}$
c – sample C - population	Covariance = $\frac{\sum(X - \overline{X})(Y - \overline{Y})}{(N-1)}$
Rs	Pearson correlation coefficient = Covariance/(s_x.s_y)

1.9.2 Mechanics

Notation	Definition
a	Acceleration (m/s^2)
g	Acceleration due to gravity (9.81 m/s^2)
m	Mass (kg)
F	Force (N)
I	Linear inertia (kg)
R	Reaction (N)

2 Literature Review

The following literature review covers a range of biological and engineering topics that relate to the multi-disciplinary approach adopted for this project. The biological basis for the project is the rehabilitation of the upper-limb and this is investigated together with related fields. Investigation of the main hypothesis introduced in section 1.1 is addressed by measuring movement, an engineering process, and this is presented in support of rehabilitation. As human participants will need to interact with mechanical measuring equipment, the human-machine interface is also explored.

Within the biological processes, investigations are grouped to understand the anatomical and sensory functions that describe the underlying mechanisms of movement, the processes of learning and rehabilitation or re-learning, and the medical conditions that affect them. The specific requirements of patients with CP are addressed to provide the scope of the immediate project and to identify specific interfacing considerations. Established clinical scales of qualitative and quantitative assessment are introduced as a background from which to determine meaningful and acceptable new quantitative measures.

Within the engineering processes section existing measurement and control strategies are investigated to establish potential solutions for new measurement systems. The latest developments in measuring upper limb motion within rehabilitation environments, and those for specific therapeutic objectives, were reviewed for application to this project and any further work that might be considered.

Human-machine rehabilitation processes are examined in order that a viable interface can be developed to benefit the user without adding too much complexity to the environment within which it is used. virtual reality environments (VREs) are investigated to determine the most appropriate and valuable content to provide beneficial immersion, without distracting the user or contaminating results with unwanted behaviours.

Given the increasing reliance on multidisciplinary working to solve existing and new challenges in health care and rehabilitation, the boundaries between biology and engineering are becoming less distinct and continue to evolve. As such, the following sections are provided as background for development rather than a precise roadmap.

2.1 Biological Processes

This section provides a brief overview of the main systems in the human body that support or facilitate movement, the acquisition of skills and the retention of learning. All of these are required in order that people can learn or re-learn skills to support their daily lives and maintain as much independence and dignity as possible.

All animals learn to perform tasks to support their existence. Most refined or practised movements reflect considerable skill and are extremely complex acts of balance and coordination. In healthy adults, most of these are achieved without conspicuous internal communication or external intervention. These are learned behaviours optimised by repeated attempts, rewarded by success or failure, and serve as self-training regimes provided that the incentive is great enough. Such incentives may be basic, such as the acquisition of food or self-preservation, whilst others are desirable perhaps developing a natural running movement into an athletic ability.

In the relatively modern world of civilised human existence, many abilities and skills remain but the profound incentives to perform and achieve them are dramatically reduced. Similarly, natural movements (that are consistent with the anatomy and native control systems in a healthy body) are being supplanted by new skills to enable inclusion in a world with rapidly advancing supportive technology. Simple examples such as climbing steps and stairs (these do not normally occur in the natural world) can be accomplished by modifying natural walking and climbing abilities. Similarly, refined and completely artificial skills such as typing, driving or playing computer games can be achieved as an extension of native fine-motor control (useful for eating and manipulating tools). However, reliance upon these new skills, to the exclusion of many others, may affect the way in which human sensorimotor performance develops and can be developed.

It is obviously beneficial to be trained to use advanced tools as progress can be more rapid through taught behaviour and response rather than through self-inflicted trial and error. Understanding of ability and performance is valuable and can be passed on to inexperienced subjects to accelerate their learning. It is not necessary to understand the detailed anatomical behaviour of the human body, how it controls itself and how it learns, in order to train, improve or extend abilities. For hundreds, perhaps thousands, of years military and sports training made extremely effective use of simple observational understanding alone. It is notable that Hamilton *et al.* [26] have investigated the effects of observation of tasks such as lifting modest weights. They conclude that a participant's own actions influence their perception of another person's actions. They note (p496) that *"observation of biological motion is known to activate different neural systems from observation of non-biological systems"*. This may have significant implications for the design of suitable VRE and the interpretation of results.

In healthy subjects the initial and desired behaviour and responses to a stimulus can be assessed, codified and trained without any significant knowledge of how the body works or how people acquire and refine movement skills. This would presumably be true if a consistently large cohort of subjects with a consistent impairment (loss of an eye for example) were needed to perform tasks in order to survive or be included in society. The loss of stereoscopic vision makes assessment of distance difficult, as depth of field would be

perceived quite differently to those with two functioning eyes. It has been demonstrated that few if any tasks, including driving a vehicle, are denied those with a loss of stereoscopic vision. The situation is not so predictable for people with unusual or complex disabilities or impairments such as CP, PD or ABI where treatment needs to be focussed on their particular and complex needs.

It is obvious that the human body is very adaptable and that desired outcomes can be achieved with a variety of approaches. It is also obvious that not all movement and skills are the most efficient, even though they may be effective. Physical and mental impairment will force changes to the way that subjects approach a task. Some tasks such as driving with a complete loss of sight would become impossible, whilst others become extremely difficult, for example grasping a cup when the brain centres controlling grip have been damaged.

Clearly, by understanding how people achieve and retain skills, changes in any part of the body and brain can be accommodated to a greater or lesser extent. Where complete recovery is not possible, aids might be offered that support isolated tasks, from simple walking frames to support balance, to interactive robotics to carry out feeding and other daily tasks. However, it is important to remember that aids, however simple or complex, are artificial and prone to failure. It would, therefore, always be desirable to allow the body to repair and restore itself first. Providing aids without rehabilitation might be considered as another taught or imposed behaviour that maintains and encourages less than optimal performance and may artificially limit recovery.

2.1.1 The Musculo-skeletal System

A study of basic anatomy shows the potential mechanics of human movement, where limits of motion are constrained by geometry, joints and tendons, and why certain movements may be more efficient than others. This system has been simulated by engineers wishing to better understand its performance and to allow modelling for predicting reactions to therapy as noted in section 2.3.2.

The skeleton and musculature provide a framework to support and move small joints, and whole limbs, and to transport the body whilst protecting the vital organs. This system contains the essential components to permit an extraordinarily wide variety of abilities between different people using the same basic biological mechanisms. Engineers would be delighted with such a self-replicating, self-repairing machine – except perhaps for the lack of any continuously rotating parts. The musculature for the legs obviously supports walking and running but many muscles support other functions as well, such as circulating blood. Whilst essential to effective movement and control, the cardio-pulmonary, respiratory, digestive, and reproductive systems as well as every other system are not necessarily significant to the understanding of movement. However, reduction in capacity or capability of these systems can adversely affect people by restricting available energy release (breathing, circulation) or by imposing limitations on daily activities due to personal dignity issues such as toileting.

2.1.2 Agonist and Antagonist Muscles

Muscles provide the forces to move limbs or to hold them stationary. In order to move a limb, the appropriate muscles contract and shorten along their length whilst others relax and lengthen. As they are attached to bones and surrounding tissue, the effect is to move a bone

about a joint. A simplified arrangement for the arm when lifting or relaxing is shown in Figure 2-1 [33].

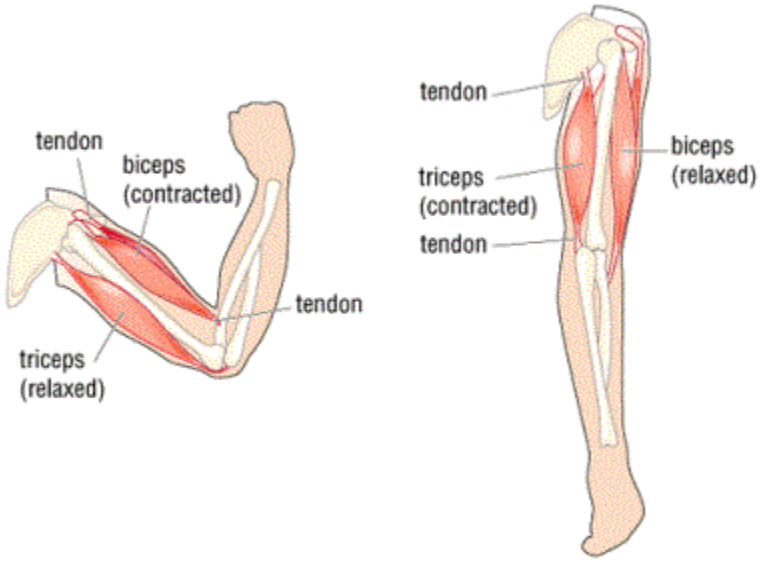


Figure 2-1 Simple Arm Movements

In order to move the hand upwards the biceps contract (the triceps are relaxed) exerting a force between the upper and lower arm bones (humerus and radius) to overcome any loads due to friction and to bear any weight. In order to move in the opposite direction, the biceps relax and the triceps contract exerting a force between the upper and lower arm bones (humerus and ulna). If the joint is to be held stationary, the biceps and triceps co-contract forming a rigid but resilient and stable beam.

Real muscles and body segments are much more complex, as illustrated by the anatomical representation in Figure 2-2 [34]. Such arrangements permit a wide range of linear motion and partial rotation of limb segments. Movements are normally limited by tendons and ligaments to protect joints and muscles, acting as stiff springs. Hence, no simple movement is actually simple but requires complex combinations of different muscles and groups of muscles.

Figure 2-2 Musculature of the Arm and Shoulder

The more complex the motion, the more complex the commands required for each muscle or muscle group. This is only part of the process, as feedback is required to control movement. Feedback is derived from a number of sources (eyes, skin, muscles and joints) but it is the

joint receptors that may provide the most valuable information. Whilst the eyes would appear to be the most important, it is obvious that controlled movement is possible without them, as demonstrated by subjects with vision loss or any movement in complete darkness. Joints contain proprioceptive sensors that provide information on the angle or displacement of the adjacent bones. The relevance and relative importance of these signals to different desired movements is learned and developed in early childhood. Similar displacement feedback is provided by the muscles through spindles that are sensory receptors within the muscle that communicate with the CNS. The combined effect allows fine and ballistic control of body segments using major and minor muscles and groups of muscles working against known rigid constraints of bones and flexible constraints in the form of tendons and ligaments.

Although it was thought that the nerves within the spinal cord (for convenience now described as the spinal cord) were primarily a sophisticated organic communications highway, this was always a flawed concept. The spinal cord actually carries out many of the control commands that were thought to be the province of the brain alone [35]. This became obvious when it was determined that it is not actually possible to process all of the necessary commands to execute a complex movement by constantly referring to the brain. It is now thought that the spinal cord will carry out multiple tasks that are formed from simple, reliable patterns of movement that have been established in the SCS. The brain may initiate a movement but then the control mechanisms within the spinal cord continue this within the limits of it training [36]. Clearly, a change in a familiar movement will require not only new instructions from the brain, but new processes within the spinal cord.

It is common to observe an initial slowness or awkwardness when new movements are required in sports training and rehabilitation therapy. This slowly diminishes in healthy subjects and efficient motion results from practice. Athletes and their trainers have depended upon the ability of the body to perform an action without the need for conscious thought and examples are common in everyday life when driving cars or climbing stairs. Highly complex coordinated movements and repeated feedback routines are carried out, seemingly without any effort. It is equally notable that these movements require re-training or extra consideration when the shape and size of the car are changed or the stairs have a different arrangement such a pitch or curvature.

2.1.3 Human Control Responses

In order for the CNS to plan and control desired movements, a form of control strategy is required. The actual process is not fully understood but has been studied for a variety of reasons from establishing norms for anthropometric data to planning improvements in athletic ability. Understanding the basic processes can assist in targeting deficiencies and expanding desired abilities. Keates *et al.* [37] identified a simple model for the *"Human Model Processor"* postulated by Card *et al.* [38]. This work indicates that the responses of able bodied and motion-impaired subjects can be modelled in a similar way:

$$\text{Total time} = x\mathbf{T}_p + y\mathbf{T}_c + z\mathbf{T}_m$$

Equation 2-1 Human Model Processor

Where: x, y and z are constants and $\mathbf{T}_p$, $\mathbf{T}_c$, and $\mathbf{T}_m$ are the times for single occurrences of the perceptual, cognitive and motor functions respectively.

Keates found that motion-impaired (CP-various, Friedrich's ataxia, muscular dystrophy, tetraplegia) users were 50% slower than able-bodied users and explains that this is most likely as a result of additional perceptual and cognitive cycles being inserted by the motion-impaired users. Relevant data taken from Keates is shown in Table 2-1.

For specific movements, Franklin [39] describes in detail the cumulative timings related to not just the mechanics of control and movement documented by Keates *et al.*, but also the time-dependent learning and progression mechanisms for healthy subjects. It is important to note that the total time identified by these researchers and others is relatively simple to determine and has been used as a valuable indicator of relative progress in simple, repeatable tasks as will be noted later in section 2.4.

Table 2-1 Typical times for planning and executing movement

Times (ms)	Card: able-bodied	CUED: able-bodied	CUED: motion-impaired
Tp	100	81	90
Tc	70	93	114
Tm	70	72	108
Reaction to simple stimulus	310	320	646

CUED: University of Cambridge, Department of Engineering [37]

2.1.4 Brain Systems

Whilst considered as a single organ, the brain is anything but a single system. It is arguably many organs that have evolved and continue to evolve to support our changing lifestyles. As with the spinal cord and musculo-skeletal systems, many parts of the brain are not involved directly in movement control (audio centres for example) but, most will interact with movement in a more obvious way than say the muscles of the legs assisting to pump blood when running in support of the heart muscles. As can be seen in Figure 2-4 [40], the area controlling movement (motor cortex) and the processing of signals (sensory cortex) are located in the upper-middle part of the brain.

The image in Figure 2-3 [41] was produced to help to explain the many parts of the brain and for which part of the body they are typically responsible. It is important to note that normal associations of the brain and related body systems do not always apply and notable exceptions appear in the literature. Mostly, this is due to formations before birth or shortly after birth when the brain is highly plastic and readily accepts new information. This is discussed briefly in section 2.5 as these anomalies should be identified in any therapy or assessment to avoid incorrect assessment or inappropriate treatment. Similarly, any post-trauma developments in the brain may result in abnormal associations that would similarly affect assessment and treatment.

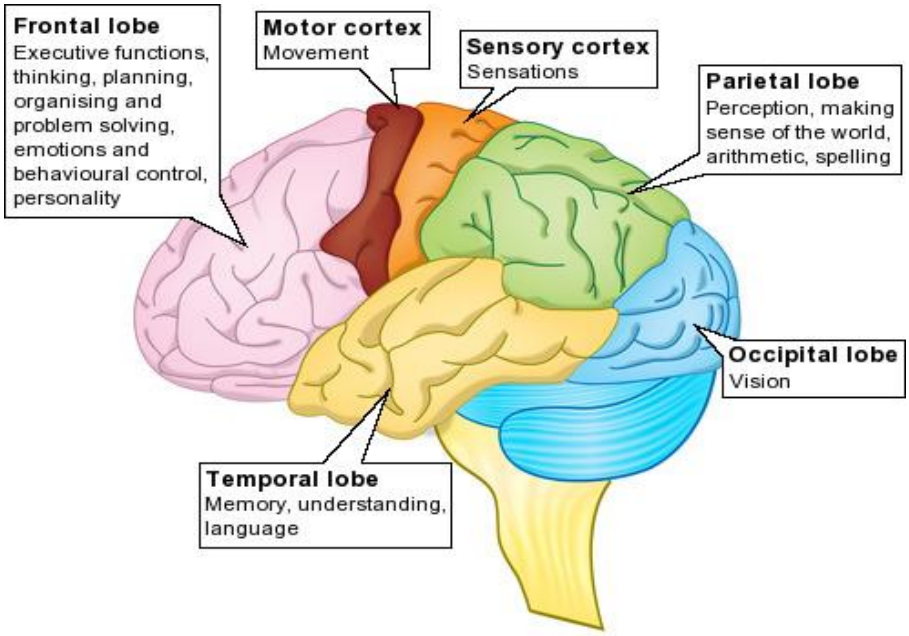


Figure 2-4 Principal Areas of the Brain

Assuming a normal arrangement of control systems, it is obvious that a significant trauma to the brain will affect any related system. Hence, for control of the upper limb significant areas are the upper-central elements of the sensory and motor cortices. Partial damage to these systems will result in partial or full loss of the related function. This is seen in TBI resulting from accident or surgery or during the progress of disease such as cancer.

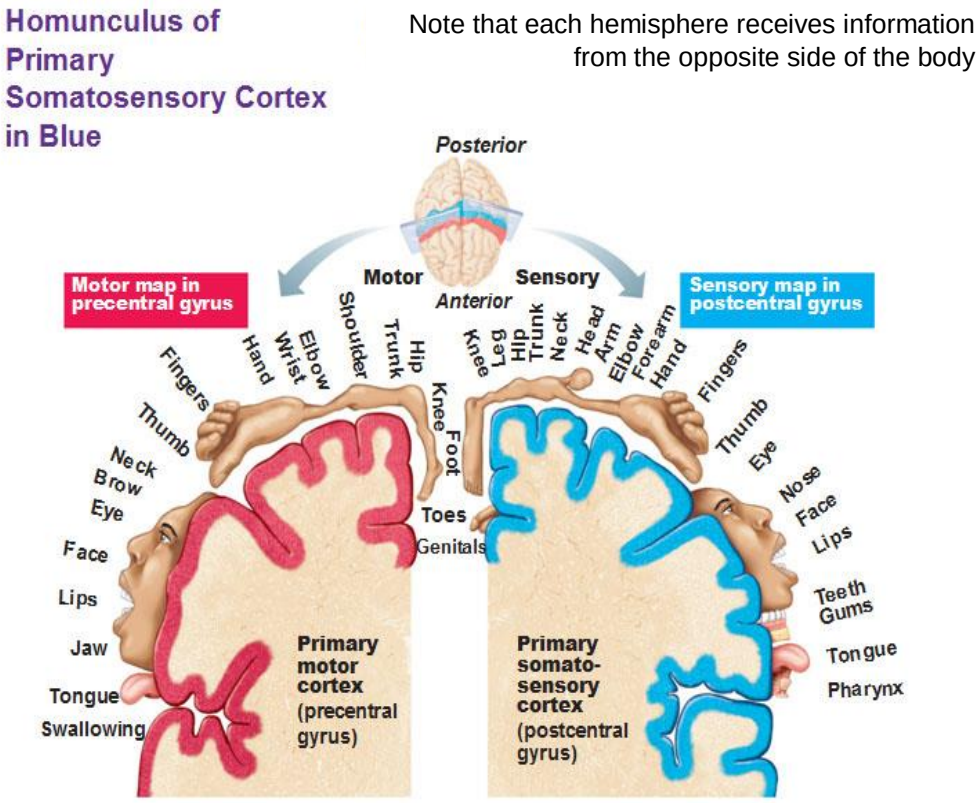


Figure 2-3 Movement Areas Associated with the SCS

Within the brain, there are multiple centres but each contains essentially the same processes for establishing and retaining the programming necessary to carry out the various tasks needed for daily living. When a movement is required, the brain gathers information from sensors (eyes, ears, joints, etc.) and plans an initial response to achieve the required motion, for example, reaching for a cup on a table. The eyes identify the target, the joint sensors identify where the body and arm are in relation to themselves and then the brain calculates an initial movement to reach the cup. Commands are sent to the muscles and movement is started. However, all of this assumes some built-in capability to know what to do with all of the information. This capability is wired into the brain by repeated experience and training, usually from infancy, as noted earlier. The actual mechanisms are not fully understood but it is reasoned [42] that chemical change in the brain becomes reinforced each time a successful sensorimotor task is attempted and completed.

2.1.5 Proprioception

The principles of proprioception were briefly introduced in section 2.1 relating to muscle and joint performance and control. In its simplest form, proprioception is the ability of a subject to identify where their body segments are in space without the need for a visual reference. The most obvious example of this is when a subject is able to touch their nose with their eyes closed. More sophisticated actions such as walking and catching a ball use similar proprioceptive sensors but with a significantly enhanced degree of refinement. Other sensors are involved, such as skin and muscle pressure, weight and balance signals, etc. However, without proprioceptive sensors and the ability to coordinate the information that they provide, most non-trivial movements would be extremely difficult to execute reliably.

There are a large number of sensors located in limb and other joints. The mapping of these to known positions of the body segments is a learned during early childhood development. Proprioceptors are typically contained in the muscles and tendons. Muscle spindles feed back information on length, tension and pressure and this informs other parts of the SCS of the length of the muscle and the velocity of any movement. The density of muscle spindles increases for muscles involved in fine movements as the CNS needs greater input in order to register small changes in the position and angle of the body segment. Similarly, for complex coordinated movements such as balancing, the associated muscles have more spindles.

The Golgi tendon organ is another important proprioceptor which is located where tendons meet muscles. This organ sends detailed information about the tension in specific parts of the muscle during a movement. There are also proprioceptors within joints and ligaments which send information to the CNS on joint angles and positions. Whether the information from these sensors will be made use of consciously or processed unconsciously depends upon their type, location and density. All proprioceptor information sent to the CNS is processed and, depending on the state of the muscle/tendon/ligament/joint, commands are sent back to the muscle to meet the desired movement. This is a high-speed communication and control process which permits rapidly changing movements in real-time.

Removing visual feedback tests proprioceptive capability and this may provide considerable insight into a subject's ability at the start of their rehabilitation, and as it progresses. It is unlikely to be a valuable test in early rehabilitation as it is a refined sensorimotor skill. However, exercises which can challenge this, such as covering the playing surface from view,

as used by van Beers *et al.* [43] and Barraduc and Wolpert [44] could be identified as extensions to simple exercises that have reached their limits.

A further ability of most healthy human sensorimotor systems is to understand and utilise information about a point outside of their immediate body. Typical examples are using a tennis racquet or a golf club to strike a ball where the contact point is not made directly with the body. The target is not always in view and the speed of action is too great to permit repeated control signals from the brain to correct in-flight movements. Some sports require a significant extended proprioceptive ability, such as in sword fencing. Here the desired target is relatively small, constantly moving and is usually only attainable by complex rapid movements that constantly respond to the other fencer's reactions. In addition, the attacking player must position their entire body to suit their most effective attack whilst maintaining a suitable defensive posture. It is notable that fencing has limited sustained enthusiasm beyond basic early practice exercises, probably due to the intense concentration and relatively slow acquisition of these complex skills.

For assessing sensorimotor capability, extended proprioception might provide the ultimate challenge. However, it is possible that many subjects would not achieve any particular ability before any impairment, so it should be viewed as a potential extension to exercises once the basic proprioceptive capabilities have been established.

2.2 Understanding Cerebral Palsy (CP)

The basis of the original research and patient group, was in support of the rehabilitation of children with CP. Hence, a deeper understanding of the issues of patients with CP is required to address their needs. This section provides an overview of the condition. It introduces the principal issues associated with the various types of CP, the possible effects on patients from childhood to adulthood, and current practice in the treatment of the condition and its associated symptoms and complications.

Early medical intervention is generally seen as beneficial although the type of treatment and its duration have been the subject of debate. There is, however, significant accord regarding the benefits of appropriate treatment and the benefit of continuous treatment at home, as well as under clinical supervision [45]. The child's family and friends can do a great deal to support and assist the development of a child with CP and any system or device that supports this would be considered advantageous.

Whilst studies are on-going concerning the reasons that physiotherapy may produce beneficial effects, there is little doubt that such therapy is seen to be beneficial both within the home and at the hospital or clinic [46-48]. The type of therapy is important and the history of treatments proposed and adopted over the last century identifies a range of treatments with variable benefits. There appears to be no clearly defined and supported treatment regime that can accommodate the needs of all CP patients. Given the diverse and often complicated nature of the condition, any single regime, no matter how complex, is unlikely to be developed. It is more likely that an adaptive regime drawing on the best treatments and, more importantly, responding to the patient's own needs and development will be the most successful.

Palsy is a short form for paralysis: a loss of the ability to move a body part. Cerebral refers to the brain and in particular to the cerebral cortex that controls movement, sensation and higher mental functions as shown in Figure 2-4. A definition by Rosenbaum *et al.* [49] suggests (p9) that:

> *"Cerebral palsy (CP) describes a group of permanent disorders of the development of movement and posture, causing activity limitation, that are attributed to non-progressive disturbances that occurred in the developing foetal or infant brain. The motor disorders of cerebral palsy are often accompanied by disturbances of sensation, perception, cognition, communication, and behaviour, by epilepsy, and by secondary musculoskeletal problem."*

The key issue is that the injury, howsoever acquired, occurs during a time of very early brain development and so is distinct from brain development in adults. The clinical assessment and any proposed treatments need to take account of the changing brain as the child grows from birth to late teens.

Whilst there are three basic classifications CP is normally sub-classified by the nature of the motor disorder, see Table 2-2. Cognitive function is not normally linked to classification and some patients may be cognitively aware and able to communicate very effectively, but are limited by motor disorders. Many children are within the normal range of intelligence. Other limiting conditions include myopia, nystagmus, squint, and unwanted eye movements which may affect movement planning and execution where visual feedback is necessary. There are a

number of other issues that may complicate treatment and assessment. These include moderate to severe learning disorders, attention deficit disorder, specific learning difficulties, and perception problems. Other motor activities such as speech eating and drinking may be affected by the failure to coordinate suck/swallow and respiratory functions.

Table 2-2 Classification of CP

Classification	Description
Spastic	Dominant population; stiff limbs, increased reflexes, static postures
Monoplegia	Single limb affected; rarely used
Hemiplegia	One side affected
Paraplegia	Lower half of body affected
Diplegia	Legs more affected than arms
Triplegia	Three limbs affected or two limbs and face
Quadriplegia	Four limbs equally affected
Pentaplegia	Four limbs affected together with head and neck paralysis
Ataxic	Volitional movements affected, tonic paresis
Dystonic, athetoid	Variable tone, unwanted movements, dynamic posturing
Source: http://cerebralpalsy.org/about-cerebral-palsy/types-and-forms/#cm; accessed 19/1/2015)	

Treatments for the varied components of CP are complex, reflecting the nature of the condition as the child's brain develops [50]. Ideally, treatments should respond not only to the patient's immediate needs such as eating and drinking, posture, fine motor control, etc, but also to the developmental needs of a growing child. There are, or have been, a variety of opinions about which is the best treatment. This diversity of opinion is not unhealthy as it continues to challenge established doctrine and modern paradigms, hopefully leading to better results for the individuals needing support.

Early treatment is generally considered the most beneficial but early diagnosis is not straightforward, particularly in babies, and hence an accurate treatment regime is difficult to decide upon. What form the treatment may take depends upon the severity of the condition, the limbs affected and the immediate or life critical needs of the patient. Treatments may range from simple orthotic devices to correct limb deformities to whole family counselling to prepare the family and child for the challenges ahead. A range of therapies may be employed individually or collectively to support the patient as they grow and the condition develops. Typically, PT is used to maintain and promote limb function and posture, ST to promote or restore language skills, and OT to encourage independence through competence with ADLs.

2.2.1 Measuring Clinical Changes

In order to determine if a chosen therapy or treatment is working for the patient, a measure of improvement or change as a result of employing that treatment is required. In order to measure changes in anything, a baseline must first be established. In basic engineering terms this is usually straightforward. For example, does the ultimate tensile strength of a metal

increase with the addition of certain alloying agents. The metal and alloys are all well understood, available in controlled forms, and procedures exist to carry out both the alloying process and subsequent testing. In CP, the baseline is inherently dynamic and the factors affecting the baseline and subsequent changes are not well understood and cannot usually be controlled. Above all, the whole process involves a sentient being with body chemistry, moods and emotions so complex that it is impossible to measure them in real-time, and controlling them would be impossible and inappropriate. So how can change, beneficial or otherwise, be measured?

A common, though not exclusive approach to measuring rehabilitation progress, is to determine a number of aims that the patient might be encouraged and helped to achieve such as ADLs. These are generally sensible and often predictable, usually intending to restore or establish some degree of independence. Examples might be to feed or care for oneself or to improve posture unaided. These are worthwhile ultimate aims but are not very easy to measure as ability changes, especially as the degree of self-control or skill is very difficult to record. Recording any sustained change over a period of prolonged treatment may be subject to inconsistency in test conditions and patient environment, both physical and emotional [48].

If the tasks or functions needed to achieve a goal could be reduced to discrete stages with clear goals or objectives then realistic, contemporaneous measurements could be established for each patient. This requires an individual assessment of the patient and what might be possible for them. From this, a series of exercises or activities can be developed which could then be used to assist in achieving one or more of the agreed goals. All of this is usually achieved by the therapists during PT/OT/ST sessions. An improvement in achieving one goal, such as standing unaided for two minutes, will determine if the activity or treatment is valuable and if the patient has reached the limit of their ability or the limit of the treatment. Clearly, any new measure of progress will need to be believable and appropriate for a range of people and abilities.

The primary objectives of this research project are to provide an accessible, usable and useful measurement tool so that a large number of people can benefit from it. In order to be accessible, the system needs to be affordable and this will inevitably limit some functionality. In their preliminary trial of automated therapy using a force feedback joystick Geerdink *et al.* [51] noted benefits to young CP patients. Although they noted improved performance with increasing assistive force, the small forces available with a commercial joystick were a significant limitation. It is important therefore, that whatever functionality can be provided is best suited to the intended therapy and/or measurement system.

The most suitable therapy or component of a therapy can be determined and assessed with suitable measurements, together with any appropriate physical and mental challenges. How this is currently achieved is not immediately clear as each therapist will develop their approach to suit their patient. Ideally, any new device or measurement would help to track a patient's progress in achieving a realistic aim. Although any kinematic measure is essentially a type of treatment gauge, it will have some intrinsic therapeutic effect. These might be related to gross limb movements during the early stages of recovery or in refining motor control as the patient recovers function.

In assessing any new regime or process, group trials are preferred. This is particularly relevant for pharmaceutical trials where reasonably stable medical conditions can be identified and

specific changes can be readily measured or implied. This may not be appropriate for assessing CP subjects. The complexities of the condition, together with the many environmental factors that affect the patients' responses, suggest that an individual goal based approach is most beneficial. Bower [52] identifies three main groups of criteria for consideration in establishing suitable therapies:

Prediction – identifying precise outcomes to maximise the ultimate potential of the child and how they function physically and emotionally. This is often dependent upon the child's future environment and opportunities and whether individual complications, such as the insidious development of musculoskeletal disorders, can be avoided.

Participation - rehabilitation requires active participation from the child to achieve a set of goals that are relevant to that child. The child is learning as they progress through their therapy and this cannot be imposed on the child.

Personalisation - Even similar therapies on similar children may be delivered very differently. Accepting the uniqueness of the individual and therapist, their particular characteristics and empathies indicates that no two therapeutics sessions will be the same.

Bower [52] summarises (p38) her concepts:

> *"In the current climate of accountability and evidence-based practice it may therefore be increasingly necessary for therapists to undertake scientifically controlled single case studies routinely in their clinical practice to demonstrate whether change has occurred over time in an individual child. This could be achieved by setting specific and measurable treatment, training or management goals for each individual child and evaluating them over time. The results might help parents, teachers, carers and even therapists to appreciate what a child can do, what a child does do, and what a child's neurological mechanisms may not yet, or ever, be ready to do. The child often knows her/his limitations perfectly well, and lack of cooperation on the part of the child often reflects this fact. Therefore the best goals are those that are realistically achievable by the child so that the child experiences success, and not failure, and parents, teachers, carers and therapists appreciate that not achieving the impossible is not failure."*

2.2.2 Similarities with other Conditions

In order that this research can understand and address some of the problems that people with SCS impairment face, similarities with other conditions or disorders were explored. The following introduces further clinical conditions that may inform the measurements and therapies being considered here.

Traditionally, patients with one condition or within a single age group tend to be treated together. The degree of cross-fertilisation of ideas and interdisciplinary cooperation varies greatly across subject groups and time. Generally, the trend is for greater interdisciplinary understanding, often driven by the need for and growing reliance on limited PT/ST/OT resources and the growing demand and reliance on devices to support treatments.

There is considerable commonality both within the direct effects manifested on the brain due to different conditions and in the resulting sensorimotor, physical and cognitive functionality. The processes whereby the patient recovers from the initial condition may vary in their detail but the external effects on a patient's abilities can be grouped as noted below.

- Change in muscle tone
- Loss of voluntary control
- Involuntary movement
- Bilateral variability
- Cognitive ability
- Identifiable recovery stages
- Plateau of recovery

Any assessment and treatment process needs to accommodate these issues, both during physical measurement and associated contact with the user, and during data analysis where patterns of behaviour will need to be identified and may be influenced by random effects.

Traumatic Brain Injury (TBI)
Any trauma to the brain, either from disease or from direct physical injury will have an effect on the body that the part of the brain controls or monitors. Similarly, adjacent areas may be affected by collateral damage from internal bleeding or necessary medical treatments including pharmaceuticals and surgery. Following a significant head injury, part of a person's brain may be rendered ineffective even though no physical injuries were sustained on the body. Similarly, a cancerous tumour may affect the brain locally and collaterally due to the swelling and displacement of tissue. Whilst some effects can be predicted, as noted earlier, because they affect a defined area of the brain, TBIs are commonly more complex. They often affect more than one area of the brain making diagnosis, treatment, recovery and rehabilitation a multi-disciplinary problem with complex and long-term changes. Recovery can be made with intensive treatment, and in children, this may be spontaneous.

Stroke
A cardiovascular accident (CVA) or a stroke is caused by a blocked (ischaemic) or ruptured (haemorrhagic) blood vessel in the brain. In ischaemic stroke (the dominant form) clots can form in the brain's blood vessels, or in blood vessels leading to or the brain, which block blood flow to the brain's cells. A similar effect is noted when too much plaque (fatty deposits and cholesterol) obstruct the blood vessels in the brain. Treatment is usually with so-called clot-busting anticoagulant drugs that disperse the clot. Treatment is often effective and patients can survive if treated promptly and possibly make a full recovery. A transient ischaemic attack (TIA), often called a mini-stroke, is a temporary blockage of blood flow in the brain that causes brief stroke symptoms. Although typically resolved within a day, TIAs are considered as indicators of a future more serious stroke.

Haemorrhagic strokes occur when a blood vessel in the brain ruptures resulting in blood seeping into the brain tissue and causing damage to brain cells. The most common causes of haemorrhagic stroke are high blood pressure and brain aneurysms. Treatment is usually by surgery to drain blood from the brain and to repair the affected vessels. Recovery is less common with this type of stroke although minor bleeds can be successfully treated if they are identified quickly.

The immediate effects and symptoms of a stroke may include weakness on one side of the body, dizziness, blurred vision, confusion and speech problems. This is due to the respective control centres either being starved of blood or being affected by swelling in the cranium.

Longer-term effects are weakness or paralysis in limbs that may lead to joint stiffness, affected speech and associated problems with ADLs. Treatments include PT/OT/ST to support or mitigate the associated weaknesses. More recently, NPT has been introduced to address activities affecting the brain that can promote recovery of function. Recovery is typically progressive and improves with therapy and motivation.

Parkinson's Disease (PD)

Parkinson disease is a progressive neurological condition caused by a loss of nerve cells in a part of the brain called the substantia nigra that leads to a reduction in the amount of dopamine in the brain. Dopamine regulates movements in the body and hence any reduction can cause many of the symptoms of Parkinson's disease. The disease does not typically cause death but symptoms worsen over time leading to complications in movement, balance, eating and ADLs. Symptoms include tremor and rigidity and slowness of movement as well as tiredness, pain, depression and constipation. The disease develops very differently between people and the course cannot be easily predicted. Symptoms can be controlled using a combination of drugs, therapies and occasionally surgery. As PD progresses, an increased amount of care and support may be required, although many people can maintain quality of life. Therapy includes PT/OT/ST in a multi-disciplinary or targeted form as symptoms develop.

2.3 Sensorimotor Learning and Therapy

Humans need to understand their environment and how to interact with it. This starts with a perception of the immediate environment and a map of the body that moves through and within it, combined with a reliable set of sensorimotor control and feedback systems. The most effective and efficient combination of these can result in extraordinary skill and achievement.

Understanding how humans carry out and act upon their perception of the world is fundamental to designing a successful ARMaT system. The following description [53] provides a useful and relatively concise summary of human perception.

> *"The study of perception is the attempt to understand those aspects of observations of the world of things and people that depend on the nature of the observer. Such understanding is obviously important to the physician, to the physiologist, and, it was once thought, to the philosopher concerned with the question of how we can be sure about the truth of our ideas. Despite these different interests, perceptual study remains predominantly psychological."*

Humans acquire information and a model of the world and their immediate environment through the five basic senses: sight, hearing, touch, smell and taste. Therapies, both human and robotic, have concentrated on the two dominant senses associated with physical and neurological rehabilitation, sight and touch. There is no reason why other senses might not be employed as well as, or instead of, these and many researchers commonly use audible feedback in exercises or games. Whichever senses are employed, their basic mechanisms of operation and human limitations must be understood as reliability of data depends upon working within relevant and predictable measurement limits.

In designing any ARMaT system, a reasonable aim would be to help patients recover or acquire normal responses to normal stimuli. These might be measured against established psychological or physical tests or against new tests on healthy, representative users to establish new baselines. But, what is normal?

Arguably, a group of people with normal sight and hearing, normal tactile, nerve, musculo-skeletal responses and normal learning abilities would respond reasonably consistently in any simple test or exercise. If a patient with CP, stroke or TBI acted similarly in the same test their behaviour might be considered normal or progressing towards normality. People are anything but normal as individuals. Normal vision has been established based on average capability to read different sizes of letters and numbers at set distances. It might also have been influenced by the ability to correct vision without enhancing or distorting it with early lenses. The expression 20/20 (6/6 in the metric system) is considered normal. Anyone with 6/6 vision can read fixed height letters and numbers at 6 m from a standard Snellen eye test chart. If someone has 3/6 vision then they can only recognise letters that might normally be seen at 3 m. But some people may have 9/6 or even 12/6 vision, which is normal for them.

Ideally, a movement standard for all healthy subjects, factored for age/sex/height/weight, would be available that describes performance capabilities and limitations. There are too many variations and exceptions to do this, but an average ability can be established, such as 6/6 for vision? How an individual achieves this average performance depends on the

individual's body, general health, age, experience, mental state, environment and exposure to similar environments. Are they operating in a safe and comfortable space? Are they at ease with the experiment? Do they understand everything? Can they be encouraged or rewarded for progress? Certainly, the testing environment could be made as comfortable as possible and hence conducive to repetitive results across a range of tests for most healthy subjects. For a child recovering from a TBI, possibly under medication, certainly physically affected by the injury to their brain and almost certainly emotionally affected, it seems unlikely that a common baseline could be found. Hence, new dynamic baselines need to be established which relate to the individual as they progress along their part of the continuum of ability noted in section 1.5.

2.3.1 The Human Sensorimotor Control System (SCS)

The brain initiates motor function based on desired outcomes, picking up a cup, catching a ball, etc. The skills required to do this are acquired and developed through training and rely to some extent on brain plasticity. This section describes how the brain establishes and retains the functionality to initiate and coordinate the required sensors and motor centres to achieve simple and complex movement. As noted earlier, it is presumed that complex movement can be generally described by combinations of instructions for simple movement.

Without some governing rules, the SCS and the variable anatomy that it controls provide an infinite number of potential outcomes. This variability is further extended when working with interfaces such as machines or mechanical-electrical devices as their kinematic and dynamic behaviour is also introduced. In the case of using a simple passive lever to measure force the results can be quite predictable, requiring only a modest extension to the innate anatomical mapping. However, sophisticated interfaces are inherently complex as can be seen in haptic devices using robotic systems. Understanding the normal human SCS is a complex task that has eluded definitive description. Understanding it's reaction and interaction with another highly dynamic system, such as a robot and VRE, may be too complex to ever really understand. These issues have been raised in various discussions on haptic VREs [54-56] but few solutions exist that can accommodate realistic VREs whilst maintaining stability over the range of human kinematic and dynamic movement. Therefore, in order to extract the most meaningful movement parameters, unnecessary complexity should be avoided.

It has been widely acknowledged that the infant brain is highly plastic in its development. In this sense plasticity is taken to mean that brain functionality can adapt and reform readily, accommodating changes that are experienced or required for healthy development. Formed with limited functionality and knowledge at birth the brain rapidly acquires skills and abilities linked to the infant's exploration of a new world, which is rich in sensorimotor stimulation. Learning to walk and talk and to recognise colours and textures is a significant achievement for the infant body and brain. All activities have patterns of sensation and response that are reinforced every time they are used. Changes in environment are accommodated by updating these established maps, extending them within natural limits experienced by the person over time. Re-training a healthy SCS response to accommodate an expanded environment can be rapid, such as learning to play tennis, a healthy development which uses specific chemical processes to form the required neural pathways in the brain.

Extreme examples of brain plasticity are noted in the use of radical surgery known as hemispherectomy which is used to control fits in infants [57]. In this procedure, half of the

brain may be removed or deactivated in an attempt to prevent life-threatening convulsions. Results have been publicised for children who have continued a near-normal life with only half of their brain still functioning [58].

As the brain develops into full maturity, the plasticity needed from birth was thought to degrade and become almost inactive. However, many new and unfamiliar tasks were still possible, such as learning new sports or languages. It was thought that these skills were really modifications of existing behaviour rather than new learning. The potential for learning previously unknown associations was demonstrated by Jäkel and Ernst [59] when they trained users in a haptic environment to associate the stiffness of an object with its brightness or luminance. They noted that this previously unused and incongruent association could be mapped onto participants through repeated training, in healthy participants. The implication here is that new SCS learning is achievable and possibly inevitable given an appropriate amount of exposure to suitable stimuli and practice. It is important, therefore, that whenever possible that any retraining is targeted to promote normal and healthy behaviour rather than self-limiting coping strategies.

Failure to recover ability following stroke may have established misconceptions of brain plasticity and may even have helped to inform early theories. If the adult, and possibly geriatric, brain has negligible plasticity then new motor functions could not be acquired following trauma. The fact that many subjects do recover limited or more significant function was treated as exceptional rather than likely for most subjects. The weight of evidence suggested that function would not normally be recovered and aids to daily living were developed to assist subjects to maintain independence and dignity.

What if duration and/or intensity of therapy for stroke patients matched that experienced by an infant learning to use its limbs for the first time? Evidence suggests that the longer and more focussed the therapy received by most stroke subjects, the greater the recovery experienced [21, 46]. Further, in post-stroke assessments, it has been noted that therapy, or continual stimulation, of the affected limb is required or initial gains may be lost [60]. In their examination of motor function recovery after stroke using functional brain imaging, Thirumala *et al.* [61] identified a variety of potential recovery scenarios which are not necessarily mutually exclusive. Similar patterns of developing function are shown in fMRI for children following hemispherectomy [57].

More recent models of the brain and its ability to adapt to changes, both minor and dramatic have suggested that the brain retains plasticity throughout adulthood and can be “re-wired” to compensate for losses in one part [62]. It was thought that redundant brain elements used to control, say the left arm, could be re-assigned to be used for the right arm [63]. This concept has a believable logic and is readily accepted. However, there is evidence [57] that other parts of the brain can be re-assigned in whole or part to accommodate losses in quite unrelated sensorimotor centres. The brain may well be able to use or re-use elements if suitable treatment and practice is provided.

2.3.2 Kinematics of Reaching Movements

Human movement is a complex and, rather obviously, personal activity which is determined by numerous factors and experiences acquired since birth. How one healthy person achieves a task may be similar to that of another healthy person of the same age, sex and size but it will

not be exactly the same. In comparison to a person who is recovering from a TBI, the task may be achieved in a very different way, or not even completed. It is this spectrum of ability, noted in section 1.5 and how to attempt to quantify it that has proved to be the most challenging aspect of this thesis.

As noted earlier, guidance on predictable movement characteristics that might be consistently applied to all normal and patient subjects is not conclusive, even if restricted to reaching movements. There is considerable understanding of normal movement, particularly for reaching tasks, although less so for impaired movement. This is rather predictable given the wide range of conditions or progress of a condition, which might affect movement, as described in section 2.2.

This section reviews some of the research into reaching tasks. It summarises patterns and useful models that might inform the justification and potentially the design of the ARMaT device and subsequent interpretation of the data that it is intended to provide.

In their work on assessing the coordination of movements van Vliet *et al.* [64] attempted to understand the reaching to grasp (RTG) movements in normal and patient (parietal and cerebellar stroke) participants. They note that the accepted movement *"transport"* (change in hand position over time) is usually indicated by predictable velocity and acceleration profiles and that both profiles are typically asymmetric about the point of peak velocity. This peak velocity in normal participants was typically identified at 50% of the overall movement duration. It represented the end of a movement that was planned with corresponding muscles being activated before movement occurred. The deceleration phase showed evidence of feedback (visual and/or proprioceptive) processes that allowed for corrections to the previously planned task. Maximum deceleration was noted prior to reaching the object to be grasped. In patient participants the velocity and acceleration profiles were notably different with smaller peak velocities and extended deceleration phases. They showed multiple corrections presumably from repeated feedback and corresponding responses to errors in the reaching movement.

Whilst the work by van Vliet *et al.* was primarily used to identify the components of RTG movements and the corresponding areas of brain activity, the initial reaching movement is directly applicable to the reaching tasks proposed for the ARMaT device. The movement phases and typical differences between normal and patient subjects can inform the interpretation of results and match similar behaviours where applicable.

In an attempt to predict and quantify typical reaching movements more comprehensively, there have been a number models proposed and these have resulted in some varied opinions on the validity of each method. In their paper Dornay *et al.* [65] review a number of these in the context of their work with primates. They note that the work by Flash and Hogan [66] on the minimum-jerk model is valuable for unconstrained hand movement from point to point but that it does not adequately address some important finding by Uno *et al.* [67]). Dornay contended that whilst the minimum-jerk model addresses the path followed in a multi-joint reaching task, leading to the prediction of realistic movements, it does not fully address what forces must be generated in the muscles. They also note other limitations such as excessive predicted dynamic stiffness.

Dornay had proposed a sequential calculation of the movement and forces whilst Uno proposed that these be computed in parallel. Uno *et al.* [67] proposed the model of *"minimum-torque-change"* which drew criticism from Flash (1990). Dornay and Uno separately examined a further model, the *"minimum-muscle-tension-change"* which does not impose a specific trajectory but is limited by a specific time. Dornay *et al.* [65] report on the appropriateness of the various models based upon work with primates (Rhesus monkeys) undertaking planar reaching tasks. These indicated that primate movements were similar to human movements and that gently curved paths were reproduced by the model they proposed. Velocity profiles were noted to be similar to those described by van Vliet *et al.* [64] for healthy participants. No motion-impaired participants were reported by Dornay or Uno.

Human anatomy and the inherent kinematics and dynamics may be modelled but it is not a simple task and people are unlikely to be so accommodating as to obey rules designed for machines, especially during rehabilitation. Harwin and Wall [68] note (p170) that *"…human arm dynamics are inherently non-linear and time dependent…"* and accept that simple models do not represent real behaviour being (p172) *"… gross oversimplification of the dynamic properties..."* providing (p175) *"adequate description but only for small movements away from the joint limits".* However, a performance measure might be identified in the absence of a detailed model [69] and might inform such a model rather than the model dictating the measurand, as has been noted in the literature.

From this brief overview of assessing and modelling human reaching movements, it is clear that considerable advances in understanding and prediction of normal human movements have been made and continue to develop. It might be concluded that no single model addresses all aspects of "typical" normal reaching movements and that the debate will continue as researchers develop evermore complex solutions to this challenging modelling problem.

Whilst there are notable developments in the understanding of the movements of motion-impaired subjects, this more variable and complex behaviour presents a considerable challenge which is unlikely to be resolved in the near future. Hence, work in assessing rehabilitation progress will continue to rely upon numerous scales of assessment and regular measurement of potentially complex reaching paths remains a valuable tool in supporting rehabilitation activities, as noted in section 2.2.1. The ability to do this rapidly and reliably with enhanced discrimination between phases of recovery is the primary objective of the ARMaT device proposed in this thesis.

2.3.3 Sensorimotor Functionality

There are many important processes that affect any investigation of, or interaction with, the human body. Planning, initiating, maintaining and completing a limb movement and the ability to repeat or adapt such movement to meet new challenges or to optimise a movement are dominant considerations for this thesis so they will be explored in some detail.

What is the best process to promote and monitor optimal rehabilitation and can this be carried out at home with limited equipment? The following sections review and examine some of the various exercise regimes that have been proposed for use in PT and OT as they are the current best practise for rehabilitation and have also been adopted with many rehabilitation devices and ART systems. Typically PT/OT exercises are intended to:

- help regain or maintain limb function
- improve mobility
- ease or improve muscle tone
- assist in sensorimotor function recovery
- assist in restoration of independence of movement
- assist in establishing and maintaining dignity
- assess progress and the need for further therapy

In addition, ART devices are usually designed to:

- reliably measure movement or performance
- be repeatable
- provide a predictable and scalable exercise
- mimic some of the normal therapy exercises.

The design of a new ARMaT device should incorporate the best of these features in support of PT and other treatments, where possible. Similarly, it should avoid unsubstantiated paradigms that may have resulted from availability of a system that was not intended for rehabilitation, such as using industrial robots, for convenience.

Accurately mimicking a therapist with a device is not possible but a simple sub-set of movements may serve as a representative sample of desired movements. Working in 2-D is a simplification of the normal 3-D world as many tasks are carried out on a table. A computer mouse is one such example with limited 3-D movement and may be acceptable if the movement or exercises are suitable.

A therapist may encourage and help train a patient to comb their own hair or to feed themselves. This is a familiar activity and one that ultimately provides them with a useful skill and requires complex SCS skills that can be adapted for other ADLs. Why then do ART devices often make users conduct perfect geometric exercises such as straight lines and circles and then measure their performance and potential recovery against such unnatural tests?

The mechanics, dynamics and kinematics of the human body are essentially non-linear, non-geometric and not pre-disposed to move in straight lines or perfect circles, however sophisticated or capable the brain or sensorimotor systems may be. Doing so may well be an indication of advanced capability but it is unlikely to be representative of ability during rehabilitation. So why are such exercises used as indicators of ability and recovery for people with known limitations in SCS and/or limb function?

2.3.4 Sensorimotor Control

The precise mechanisms used to control the upper limbs are not well understood despite considerable research. Different models have been proposed (see section 2.3.2) which might describe and hence predict movement and control of movement such that these might be replicated with electro-mechanical devices [68, 70] and permit the design of a suitable measuring system. Wolpert [36] has proposed a comprehensive model that addresses both kinematics and dynamics in healthy subjects. The more complex issues of sensorimotor re-

training of basic movements require a far deeper understanding than currently exists but, the work by Wolpert allows realistic models to be evaluated.

Before expanding upon complex SCS functions, it is instructive to review the basic models that have been proposed and developed to help describe human movement. These are summarised below:

Feed-back Control

Much research has been based on the presumption that human motor behaviour is dominated, if not fully reliant upon, feed-back control. A quotation from Norbert Weiner's C*ybernetics* published in 1948 [71] illustrates (p7) this well and places a timely reminder of development in this area, which has been fragmented for many years:

> *"Now suppose that I pick up a lead-pencil. To do this I have to move certain muscles. However, for all of us but a few expert anatomists, we do not know what these muscles are; and even among the anatomists there are few, if any, who can perform the act by a conscious willing in succession of each muscle concerned. On the contrary, what we will is to pick the pencil up. Once we have determined on this, our motion proceeds in such a way that we may roughly say that the amount by which the pencil is not yet picked up is decreased at each stage. This part of the action is not in full consciousness. To perform an action in such a manner, there must be a report to the nervous system, conscious or unconscious, of the amount by which we have failed to pick up the pencil at each instant. If we have one eye on the pencil this report may be visual, at least in part, but it is more generally kinaesthetic, or to use the term now in vogue, proprioceptive."*

Weiner expresses this simple action as a classic closed loop feed-back control system where the reduction of error (failure to reach the pencil) is used to plan the next movement. Having moved again, another error reading is taken and this is used to plan the following movement, and so on. He also identifies that feedback on arm position is not reliant on visual cues alone but that the limb itself provides information. What is not explained by Weiner's illustration is the contribution of any learned or pre-programmed activity within the initial movements of the arm which may not be subject to feedback control signals.

Feed-forward Control

The concept of feed-back control is predictable and readily demonstrated. However, it is unlikely that all movements are capable of being carried out with full or even partial real-time feedback. There is considerable debate [36, 39, 72-74] about whether the SCS operates as multiple high-speed feedback circuits relying on very fast visual and neural processing or whether other control mechanisms are required, and in some cases dominate.

The control signals required to do something as commonplace as moving to catch a ball require multiple visual cues, thousands of coordinated muscle control signals, gross limb movements and fine motor skills; all in a fraction of a second. It has been demonstrated [39] that the amount of sensory input, control signal output to all the individual muscles, and feedback needed to achieve such tasks is beyond the capability of a human feedback system. Hence, some parts of the whole action of catching the ball must be carried out at a higher level, as learned or pre-programmed muscle group activities. Such actions might be initiated by visual information but no further feedback of position to the brain is needed to complete

the basic movement sequence. Hence, feed-forward control is likely to play a significant role in all movement. One possible exception would be if multiple, as yet undetected, signals were being exchanged to carry out hundreds of closed loop control commands. This possibility has not been identified in the literature to date so will not be explored further in this thesis.

Returning to Weiner's example of feedback control, the time required for someone to pick up a pencil is relatively large compared with that available to an athlete, or concert pianist when performing their most complex activities. There must be some other mechanism supporting complex tasks and this is probably true of every action irrespective of complexity. A healthy subject can find a pencil with a single visual cue. If too much time elapses after closing the eyes then the exercise becomes less reliable. However, the pencil can still be located even if the relative position of the body to the target is changed such as rotating in a chair. Adjustments to the planned arm reaching movements are made based on internal models of the body which are interpreted and manipulated to suit a changed situation. If the action is delayed or the body position is adjusted too far from the internal mapping the pre-programmed activity and map upon which it relies (which is a short-term open loop control pattern) is lost or diminished.

Intrinsic or Extrinsic Planning

Attempts to understand and define how a simple reaching task is achieved continue and a number of potential explanations are becoming accepted. Kawato [75] attempted to draw a number of these possible explanations together but still acknowledged that they do not explain all possible actions completely. By understanding how most people do achieve such tasks it may be possible to understand why some people with injuries to the SCS cannot achieve this. Further, if they cannot do so, but exhibit certain patterns of motion attempting the task, might further information be deduced from these patterns to predict areas of injury and to optimise potential recovery routes? If this were true then recording such patterns faithfully and accurately would be essential and is a guiding principal in this thesis.

This intrinsic model suggests that people identify an object in front of them and plan a path to the target using a model of the joints and body segments needed to achieve the task; a feed-forward, open loop control strategy. In contrast, an extrinsic model would suggest that constantly updated external visual feedback is used to adjust the required movement paths based on error correction; a feed-back, closed loop, control strategy.

Goodbody and Wolpert [76] identified patterns of movement in healthy participants which suggested that planning and execution of reaching tasks could be carried out using either intrinsic models or extrinsic modelling, or a combination of both. They conducted a number of experiments using non-haptic pick and place tasks to isolate the mechanisms at work in these simple tasks. The tests involved healthy participants who were asked to carry out simple point-to-point tasks under conditions of normal or displaced visual feedback. They also noted (p222) that the observed natural curvature of the path might be a consequence of a *"misrepresentation of intrinsic position".*

As noted earlier there is some division of opinion about how simple reaching tasks are achieved. Even a simple 2-D reaching task requires a multi-joint arm movement and this movement is notably not a straight path with minimum path length. This was investigated by Bossenkool *et al.* [77] who concluded that most paths in healthy participants are curved, variable in speed and vary between the participants, length and angle of reaching task. Where

motion is slow, the maximum velocity is typically earlier in the movement whereas in ballistic movements, the maximum velocity occurs later in the path. However, path curvatures were virtually unchanged despite a doubling of speed. They concluded that curved paths are not due to visual misperception of straight lines; rather they are a natural feature of multi-joint movements and their supporting planning.

Reaching movements are effectively mirrored between left and right hands about the mid-sagittal plane. This indicates that anatomically similar, non-neurologically impaired subjects exercise similar reaching movements which are not affected by the dynamic properties of the arm. In effect, the SCS models the dynamics of the arm and joints and compensates for changes in the desired velocity of a reaching task.

2.3.5 Models for Learning Movements

The way in which humans learn movements has been the subject of considerable investigation in healthy subjects. What learning is lost in subjects with TBI is rarely identifiable at an organic level and is therefore usually classified by reference to loss of function. Various scales of ability can be used to provide an approximate measure of these. The work of neuroscientists such as Wolpert and his associates has provided a profound insight into the most likely mechanisms of sensorimotor control and learning which begins to explain the observed performance of normal and impaired movement.

The findings by Wolpert *et al.* [36] gather evidence from diverse research and propose that motor learning and sensory awareness are potentially mutually supportive in their development and maintenance. That is, sensory systems will, predictably, support motor learning but also that motor learning can change basic sensory processes. This has significant implications in the form of rehabilitation and assessment that might be used for a subject with sensorimotor deficits.

Wolpert *et al.* suggest that there are three basic forms of sensory computation that help improve a subject's interaction with their environment. This is necessary as the information from the various sensory systems can be delayed and corrupted by unwanted inputs or noise originating from within the body, or externally from the environment. Firstly, the various streams of information can be combined to produce an optimal solution that minimises the effects of noise. This revised model can be further refined by a statistical view of potential outcomes using Bayesian inference. Finally, the internal model of the body can be combined, again using Bayesian inference, to determine the evolving state of the body within its environment. This view has permitted the wider consideration of the impact and interaction with cognitive and perceptual elements of a movement or task.

In addition to the feed-forward and feedback control systems noted earlier, additional control exists at a biomechanical level involving the form or stiffness of a limb, typically by modifying the compliance of the limb during an action. By accessing the necessary parts of the sensory and control systems to minimise noise, new or refined models of movement and the environment can continually evolve. This is most notable in slower control loops (supraspinal) rather than high speed monosynaptic reflexes.

Wolpert suggested that the optimum solutions learned are based upon a goal, such as selecting an object, being reached with *"minimum intervention".* Task-orientated movement and models are beneficial and they ignore task-irrelevant signals which will result in sub-optimal

movements. These need to be learned by extending known models and by trial and error when engaging with new tasks. The impedance control paradigm is thought to be the most likely to result in optimal movements within any uncertain environment or task.

Three forms of learning are proposed by Wolpert *et al.* [36] which allow the human SCS to gain advantage over its environment:

Error-based learning relies upon noting the error between the intended task and the resultant action. The corrections planned and executed in subsequent actions use the gradient of the error to determine a solution that results in a zero nett error. Although repetition proves valuable in this process, a single trial has been noted to result in adaptation. As the cerebellum is involved in this form of learning, damage here can result in significant loss of rapid adaptation.

Reinforcement learning is a natural progression from error-based learning as the latter can only reduce the nett error of a movement and not select the optimum movement. Hence, another variable is needed to advance a movement skill. As this requires effort, there must be a form of reward for the SCS to keep trying to improve a task such as throwing a ball at a target. Hitting the target is achieved by reducing the error and hitting the target quickly might be a result of reinforcement.

Use-dependent learning is observed when the SCS changes by pure repetition of a task or movement. It may not be beneficial to do so and it may occur in the absence of any planned progress. Good behaviours could be changed to less beneficial ones and vice versa.

Wolpert *et al*. also report on a recent development which has demonstrated observation-based learning although this behaviour and the techniques to exploit it have been noted by sports trainers and teachers for millennia. Put simply, the action of observing is a learning process in itself. Hence, if a subject observes an action, lifting a weight, they observe and map errors which they can then use in their own actions.

2.3.6 Re-learning Skills

Understanding how skills are learned initially and maintained through experiencing varied environments helps to formulate an understanding of how a patient might re-learn such skills following injury or disease. It may be sufficient to accept that this can be achieved rather than maintaining dated paradigms that certain abilities will never be realised or recovered. As noted in section 2.3.1, recent studies confirm that considerable rehabilitation is possible for many patients given sufficient time, effort and resources.

In healthy participants, new motor skill/path learning has been examined using robot-mediated exercises to assess how and what types of learning are possible and what might perhaps be normal. In their work with the Sensable Phantom™ robot Liu *et al.* [12] examined the potential to learn a novel movement whether this was guided by the robot or just following demonstration in a 3-D VRE. They concluded that whilst path tracing ability improved following robot guidance (not forced movements), the tracing error rapidly increased when the guidance was removed. They also noted that this tracing error was consistent with what they (p37) termed *"a systematic evolution towards an "attractor path".* They concluded that haptic guidance provided a large short-term effect which was followed by slower longer-term learning provided that repeated exercises were maintained. They also

noted (p40) that *"forgetting"* the learned novel path motor skills was common even with *"substantial training".*

The potential of *"attractor paths"* probably relates to the reward driven learning noted by others [74, 78] where paths may be smoother or require less effort when followed more naturally by the user as noted in section 2.3.2. These paths are probably those mapped from years of refined reaching movements in the real world and are therefore well established and are probably the default solutions despite repeated re-training. Liu *et al.* also noted that the *"attractor paths can be altered with training"* and that some of their effect might be related to the paths required to navigate commonly perceived shapes which participants are known to *"regularise"* to make them more symmetrical. This is a key element of rehabilitation in that the user's map of the world and how they interact with it can be relearned in established, normal subjects. Provided that the neurological potential exists, they can be relearned following TBI as well.

2.4 Measuring Rehabilitation

The literature indicates that the CNS, can learn and relearn movements and coordinated sensorimotor tasks from birth through to healthy old age. It would appear to be possible therefore, in all but the most extreme cases, to relearn functionality in injured body and brain elements. If the training (therapy) and motivation (personal and therapist) is sufficient and appropriate for sufficient time, then relearning and long-term retention should be possible.

How much functionality can be relearned and the best way to facilitate this is the subject of considerable research. Assuming that no lasting damage is present in limb segments or nerve pathways, the potential for rehabilitation may be significant. To understand how best to facilitate rehabilitation, a greater understanding of how basic sensorimotor learning and operation is required and this follows in the next sections.

The following terms are taken from Magill [79] and are summarised in this section. Magill discusses a wide range of skills and tasks that are used or are available for use in healthy sensorimotor performances, such as sport. He also adapts this understanding to rehabilitation and establishing of skills following injury or retraining. Whilst there are some differences in approach to a healthy subject learning a new sport and that of a subject requiring rehabilitation, (injured muscles and bone need to heal before exercises can begin), the process is similar and relies on brain plasticity.

In the context of this section, Magill defines (p7) a skill as a motor skill which is an *"action or a task that has a goal and that requires voluntary body and/or limb movement to achieve the goal"*. Reaching for a book or catching a ball is a skill that may be achieved in a variety of ways using a combination of body segments and control strategies. Combining skills and refining them allows a regular or improving ability to perform tasks. This may result in being able to run faster or further or to play a piano more fluently. In the first case, performance can be assessed accurately using temporal measures such as lap or race times and is clearly quantitative. In the latter, the results are more qualitative, requiring a judgement which may not be easy to transfer and hence may not be universally accepted. A simpler task, such as picking up a cup, can be considered successful when it is achieved on the first attempt and without spilling the contents. Picking it up more quickly would not necessarily be of any advantage. All of these skills demonstrate an ability to perform useful or desirable functions but their outcome measures are very different.

To better understand a skill and how it is developed, Magill suggests that they can be classified, as noted below. However, it is important to understand that no single skill exists in isolation. All skills will, at some point, join with other skills so there is a continuum of ability, noted in chapter 1, just as there is a continuum of natural colour or sound.

Quality of Movement - There are two commonly accepted movement types, gross and fine. Gross movements involve large muscles or muscle groups and may be defined as movements requiring little precision but still requiring significant coordination to achieve a smooth and intentional motion. Walking or throwing a heavy object would be considered gross movements. In contrast, fine motor skill use smaller muscles or groups of muscles and they are directed at achieving small movements with precision. Writing and painting require high precision and refined hand-eye coordination. Clearly, other movements require a combination of both gross and fine skills. Throwing a dart or ball to strike a chosen target may require

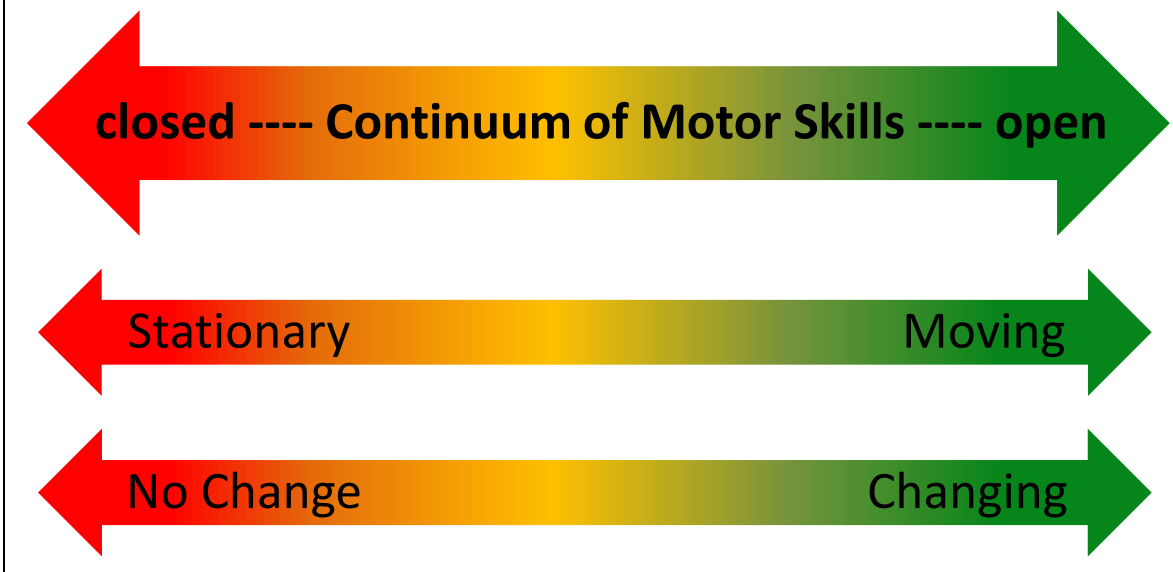
gross movements initially but the accuracy of the throw might be dictated by fine motor skills as does balance in dance or athletics.

End Points of Movement - Movements can be identified as having a start and end, even if there were preceding or subsequent motion. Simple movements such as striking a key of a computer keyboard or drawing a line are discrete skills. They start and stop at clearly identifiable points that define the success of the motion. These discrete skills can be joined to form serial skills such as writing a letter from the alphabet. Less formal end points or those that are dictated by external forces can be described as continuous skills. Such skills are typically repetitive, such as running or steering a car. Here skills are defined by the continued success of the action rather than individual movements.

Stability of Environment - If the environment surrounding a person using a skill is stable then the skill can be predictable and can be described as closed. Activities such as playing cards are predictable as little will change during the action of picking up or laying down cards. In contrast open skills require real-time adaptation in order to achieve success. Cross-country running requires constant adjustment to the terrain and surface as does playing tennis.

Self or externally-paced skills are terms that are closely related to closed and open skills. Selecting a playing card is directed by the player in their own time and hence is a closed, self-paced skill, as are many industrial tasks such as machining. Running to catch or strike a ball is a response to a spontaneous external stimulus. This requires open, externally-paced skills to achieve success. These skills can be placed on a skill continuum as noted in Figure 2-5, adapted from Magill.

Figure 2-5 Continuum of Motor Skills



In Figure 2-6 the four skill categories from Figure 2-5 are described with examples for using a desktop computer, again adapted from Magill. This shows how the required skills vary to meet the intended activities and the potential complexity or difficulty of the task.

Figure 2-6 Motor Skill Categories Applied to Desktop Computer Activities		
	Skills Requiring no Change	**Skills Requiring Constant Change**
Stationary Skills	No change is required in a static environment to meet the objectives: pressing the return key on a computer keyboard when a repetitive sound is heard.	Change is required but in a static environment to meet the objectives – pressing an arrow key on a keyboard to select a moving target on a PC game.
Moving Skills	No change is required to address a moving object: a single key strike to hit a pendulum target when it passes through a fixed point in a game.	Change is required to address a moving object: using a joystick to hit random targets in a PC action game.

2.4.1 Measurements of Motor Performance

In order to assess the development, or otherwise, of a motor skill, a reliable measurement of performance is required. This could be a number of quantitative or qualitative measures but they need to be meaningful and reproducible. As with motor skills, performance measures can be categorised to assist basic understanding and to devise suitable performance measures that can assist the assessment of therapy. Magill identifies two simple categories; response outcome measures and response production measures. Outcome measures are the more simple and reliable of the two and have been the subject of numerous studies [80], particularly earlier studies where more sophisticated measurements were beyond the technology available at the time. Modern studies will often include at least one of these as they can provide a rapid and often intuitive result [81]. The author has expanded upon the categories proposed by Magill to include categories that more closely identify the potential for assessment in this project. The expanded categories are summarised in Table 2-3.

It could be argued that simplicity may also limit sensitivity and/or scalability. For example, in a time on/off target task it may be impossible to make a new task predictably twice as difficult as the first. Speeding up a rotating target would be possible, but might be limited by physical constraints such motion perception. Also, it is not immediately obvious that doubling the speed of rotation represents a doubling in difficulty or subsequent achievement. Modifying the direction might be an alternative challenge but the results might be significantly affected by inertia in the system, which might not be measured or allowed for.

Production measures are more sophisticated and generally more sensitive and scalable although they are still limited by physical constraints. Being more complex they can be subject to greater measurement errors which might not be related to the subject's actual performance. Many of these measures are made in real-time and the synchronisation of stimulus and response is a typical source of error. However, production measures have become more popular as high speed data capture and storage becomes more accessible and reliable. High speed electronics permit the simultaneous measurement of a variety of raw production measures and these can be developed into compound measures which combine different measures.

Table 2-3 Motor Performance Categories

Category		Typical Measures	Typical Performance indicators (units)
Response Outcome Measures	**Temporal**	Time to complete movement (s)	Lap time; time to throw three darts
		Reaction time (ms)	Time from green light to starting movement; time from buzzer sounding to starting game
		Time on/off target	Time a pointer can be maintained on a moving target (s)
		Movement time	Time to execute a planned movement (s)
	Error-based	Performance error	Distance from target (mm); lag behind target (mm)
	Success-based	Attempts to complete task	Number of attempts to reach and grasp a cup (attempts)
		Successful attempts	Targets destroyed in a PC game (targets)
	Ballistic	Distance	Distance object was thrown (mm)
		Contact	Repeated striking of a fixed target (strikes)
Response production measures	**Kinematic**	Displacement	Path length travelled by a limb segment to reach a target
		Speed	Displacement divided by time taken to reach target (m/s)
		Velocity	Speed at a given angle (m/s)
		Acceleration	Rate of change of velocity in accelerating or decelerating to reach an object (m/s^2)
		Joint angle	Angle between two limb segments at maximum speed (rads)
	Dynamic	Displacing force	Force exerted against a joystick in a haptic game (N)
		Maintaining force	Force needed to hold a steering wheel centred against variable road conditions (N)
	Electro-chemical	Electromyography (EMG)	Muscle firing time in a spontaneous or planned reaching task (ms)
		Electroencephalogram (ECG)	Characteristic brain response to a planned activity (electrical patterns)
		Functional magnetic resonance imaging (fMRI)	Changes in brain activity in response to a real-time stimulus (brain images)

Adapted from Magill [79]

2.4.2 Response Outcome Measures

Typical applications for most outcome measures are obvious from the descriptions in Table 2-3. However, some require further clarification to identify their importance and the opportunities they offer for upper limb measurement.

Temporal Measures - These are the most varied but generally the easiest to measure and monitor and have therefore found considerable use in many different rehabilitation studies and applications and these are introduced and described in more detail in chapter 4.

Some measures such as lap-times for running or swimming, or movement times in a placing exercise are obvious and intuitive measures of performance. Being based upon speed (time to reach a common distance) they are most suited to a healthy subject and may be inappropriate for assessing rehabilitation when movement is limited. However, progress is readily assessed and feedback to the subject can be rapid with clear objectives, both being very desirable.

Time on/off a target is easy to measure but the actual measurand is more complex. This may vary from a simple rotating target and fixed path to random paths providing increasing, and potentially impossible, challenges. Typically such tasks require good hand-eye coordination and reasonable physical capability over normal reaching distances. The most simple require little prompting or planning but may test endurance and attention rather than SCS processes. More complex multi-path tasks require multiple planning strategies in real time and may be mentally tiring if attempted for too long, potentially masking any changes. These tasks are readily scalable to provide a continuum of challenges from a common learned response. The response time, discussed below, is important as each new path is potentially a new movement and the challenges can be significant.

Response time is not only easily measured but it also intuitively appropriate as a measure of performance for many everyday tasks. Although a simple measurement, it is actually composed of various prompts, and activities as noted in section 2.1. For performance measurements, it can be can be broken down into seven components, as noted in Figure 2-7, adapted from Magill.

Figure 2-7 Components of Response Time

Activity controlled by:						
External Agent Prompt			**Subject Performance**			
Warning	**Anticipation time**	**Stimulus**	**Reaction Time (RT)**	**Initiate response**	**Movement Time (MT)**	**Terminate Response**
Countdown or verbal notification	Subject prepares for known or unknown movement	Buzzer sounds or target appears suddenly	Subject makes decisions and plans movement	Movement is started	Movement is executed	Response is completed

It can be seen that the reaction time (RT) and movement time (MT) are controlled by the subject with the external agent (experimenter or system) providing the necessary prompts. Hence, the subject's performance can be assessed by measuring a simple response time, or more comprehensively by the RT and MT measures. The prompts can be varied to isolate

factors in an experiment such as premature movement based on familiarity with the task. Simplistically, RT may be closely related to CNS capability or impairment and MT to physical capability; both may be significantly affected by environment and motivation [21, 48, 82].

Error-based - These may be measurements of distance from a target, such as throwing darts at a board or following a rotating target. Progress would be measured as a reduction in the individual or aggregated distance over a number of trials. Again, these are relatively simple to measure and are scalable and continuous, allowing both gross and fine improvements to be identified. Similar tasks may be devised to maintain a deliberate distance from an object, which changes the emphasis but not necessarily the skills involved. As with temporal measures, maintaining or minimising a distance in real-time with changing targets or objectives challenges the user's mental and physical coordination and capabilities in a predictable and scalable manner.

Success-based - Whilst temporal and performance measures are scalable and continuous, success-based measures are essentially ordinal in nature. That is, the number of successes must be discrete and hence may not have a continuous relationship with ability. Hitting all of the targets or doing so without any initial failures may be a quick measure of ability with ready feedback but, the measurand is dictated by the detail of the task. A complex task may require as much skill as a temporal or error-based task but the results are less finely reported. For example, if there are ten targets, the best score is ten. Missing one target results in a 10% reduction in score but, it is unlikely to be accurately correlated with a 10% reduction in ability. Adding targets may improve the apparent continuity of measurement but unless the movement is refined as well, the results will be essentially ordinal and less sensitive than other measures. Repeated measurements (using means or median values) taken over several tasks can be used to minimise these effects provided the task is not too taxing.

Ballistic - These may be considered measures of ability such as strength or endurance. Throwing similar sized objects of different weights will challenge rehabilitating muscles and improvements in the distance thrown would suggest improved physical capability and perhaps technique and planning. Similarly, repeatedly striking or kicking a fixed target would demonstrate endurance and possibly refinement of movement, indicated by improving the number of strikes in a set time due to better coordination. They are generally not scalable or continuous measures.

Response measures are not generally complex and results can often be reported using basic descriptive and inferential statistics.

2.4.3 Production Outcome Measures

Production measures are inherently more complex to gather and may contain many identifiable variables of performance in the continuum of ability introduced in chapter 1. These may include coordination, physical and mental agility, endurance and strength in varying degrees as well as motivation and environmental responses. Separating the principal elements of each of these potential contributors is complex and difficult to define in real-time. Generally, post-processing of results is required and hence feedback may be delayed and some potential value to the user may be lost. However, many of the parameters are intuitive and can be reported upon as with response measures. For example, the task may be to hit a

series of targets, typical for many response measures, but the measurands might be the velocity, force or accelerations employed to do so. Immediate feedback is available (targets hit) but the deeper analysis of performance is far more complex and potentially more valuable as a refined indicator of progress.

Kinematics - Kinematics is the study of movement alone. Forces can be ignored although in all but a few highly specialised cases forces are actually involved and may dominate movement. Usually gravity and friction have to be overcome, even if merely compensated for, in addition to bearing the weight of body segments. Kinematic measures can be used to describe the quality of the movement rather than basic records of movement. For example, a subject may refine a skill to improve successful target strikes. A response measure may show a crude improvement for example, reaching six targets rather than four. However, an analysis of path length, velocity, acceleration and joint angles would show changes in the way the subject approached and completed the task. Close observation by an experienced PT/OT might note some of these changes and may identify more successful strategies. However, small but important changes may be missed.

Dynamic - Dynamics is the study of forces in motion. As with kinematic measures, dynamic measures have the potential to describe the quality of the movement in fine detail. Haptics are a typical application of dynamic measures which might record the range of forces that a subject uses to throw a ball, rather than the distance achieved. If the ball can be thrown further with less force, a clear refinement has been achieved, enhancing this motor skill. As the kinematics of a dynamic movement are usually recorded simultaneously, dynamic measures might be considered the most advanced form of measurement. In order to capture all the kinematic and dynamic information, devices require advanced sensors and processing. As this is normally carried out in real-time, the equipment is very complex and normally expensive. This is a significant limitation to mass deployment of equipment and systems.

Typically, the full potential of dynamic challenges are not possible in a measurement environment. For example throwing a ball at a target requires gross and fine motor skills, judgement of distance and weight, error-correction from unsuccessful throws and physical and mental agility. Although it may be very difficult (or unnecessary) to record dynamic measures – forces in each limb segment are very informative but nearly impossible to measure – Kinematic measures could be used to infer ability by changing the weight of the ball. Haptic devices could simulate this and other more complex interactions but their cost precludes general use. A simple compromise would be to adopt a semi-dynamic measure using different fixed weights or friction, as required by the task. Suitable analysis should be able to isolate the subject's kinematic behaviour to the varied dynamic challenges.

Electro-chemical - The two most common electro-chemical measures are Electromyography (EMG) and Electroencephalogram (ECG), both of which detect electrical charges within the tissues of the body, be they muscle or nerve, which are created by chemical changes in the tissue. As with the other Production measures, these are scalable and very sensitive to changes in physical and mental ability, often being used as a diagnostic tool to detect and monitor injury. The EMG signals can support analysis of muscle activation time in most assessments and can be useful in isolating issues with nerve impulses reaching the target muscles. As such it is a crude measure of performance and may be likened to a response measure. It could be identified in Figure 2-7 at a point before movement has started. In fact the pre-movement or

anticipatory EMG signals are extremely important in assessing the multi-joint interaction torques required for complex multi-segment reaching tasks as noted by Gribble *et al.* [83]. All such signals are inherently noisy and extracting "true" signals indicating actual continuous movements, rather than the onset or cessation of movement, can be extremely difficult.

Functional magnetic resonance imaging (fMRI) is probably the most sophisticated system of measurement, but with the furthest to be developed if regular use is to be possible. The potential for the system is significant as the real-time activity of the brain can be recorded without intrusive probes. The sensorimotor areas of the brain can be mapped throughout rehabilitation and inferences can be made on the efficacy of a treatment. Work to date has been limited by the cost and physical size of the required systems and the restrictions on movement within the scanning envelope.

There are no ideal measures for any application and a compromise will always be needed between competing requirements such as sensitivity, ease of measurement, cost, physical intrusion and reliability, etc. Table 2-4 shows a summary of the principal considerations when selecting and using a measure to assess rehabilitation. The rating included for each measure has been offered by the author based upon the literature reviewed and observations. It should be noted that more complex assessments, such as those used in the clinical trial described in section 5.1 will typically require more than one measure.

2.4.4 Measures of Rehabilitation

The upper limb is a complex assembly of linkages and supportive tissue with multiple degrees of freedom. It has variable geometry between subjects, with age and between left and right sides. The combination of upper limb and shoulder is capable of exerting considerable force and rapid motion whilst also being able to control very fine and delicate movements. In keeping with the rest of the body, and nature in general, it contains no constantly rotating parts or perfect linear actuators. All movements are made using combinations of partial rotations and partial bending at joints. Movement effectors are non-linear muscles or groups of muscles which are constrained by non-linear ligaments, variable bone geometry and multiple external factors.

Reliable movement of the upper limbs is essential to support an independent life. Similarly, rehabilitation of the upper limbs can contribute to the overall recovery of sensorimotor function in patients following ABI [22]. Whilst many aids can support mobility following damage to the lower limbs, improving the use of the arms and hands makes all tasks more manageable and productive.

In order to understand how best to measure and provide upper limb rehabilitation a simple movement should be selected that is both meaningful to the user or patient and valuable as a therapeutic exercise. Reaching movements are typical of these and have been used as the basis of a large number of research trials as noted in Table 2-5. They are simple to produce, meaningful to ADLs, visible to the user and typical of modern human-computer desktop interactions.

Table 2-4 Overview of Measures and Selection Considerations							
Considerations in selecting a method of measurement. (When rated 1-5, 1 is the lowest level for any criterion)	**Response Measures**			**Performance Measures**			
	Temporal	**Error**	**Success**	**Ballistic**	**Kinematic**	**Dynamic**	**Electro-chemical**
Set-up complexity	2	2	1	2	4	5	3
Sensitivity	3	3	1	1	5	5	3
Repeatability	4	4	2	2	5	5	4
Reliability/noise	4	4	3	2	4	4	3
Scalable	3	2	1	1	5	5	4
Continuity	4	3	1	2	5	5	4
Intrusion	1	1	2	2	1	3	4
Equipment complexity	3	3	2	2	4	5	4
Cost	1	2	1	2	4	5	4
Analysis complexity	2	2	1	1	5	5	4
Feedback readily available	3	3	5	5	2	2	2
Interpretability by users	4	5	5	4	3	4	2

2.4.5 Reaching Movements

Examination of the subtle movements needed in, say, picking up a cup or pressing a light switch reveals a multitude of movements to achieve this simple objective. The different approaches (mostly unconscious) between people might be attributed to variations in physiology and the surrounding environment or they may be the result of good and bad experiences when younger. Clearly, the complex dynamics and kinematics of the upper limbs and shoulder provide for many successful pathways to the cup or light switch. The contribution of the upper body, head and possibly the lower body multiply the possible patterns of muscle and body segments significantly.

Methods exist using cameras [84] and have been used to assess motion paths which can be categorised and used as baselines for further experiment and treatment. These systems typically rely upon large data sets covering prolonged and continuous or periodic motion to establish stability of their algorithms. However, variable reaching movements are essentially, discontinuous and could be described as ballistic for at least part of their range, see section 2.4.1. Recording such movements reliably has not been achieved without considerable expense and then with some loss of start and end point data (personal communication: [85]).

Clinical exercises may be grouped into two areas although there is obvious interaction between them. The first group are those exercises needed to regain basic mobility or to promote healthy tissue maintenance. These might be as simple as lifting exercises to prevent muscle wasting or more complex gait improvement or postural stability regimes. The second group would include exercises that are targeted at recovering or maintaining CNS and SCS function following injury to the brain. The two categories of exercises need not be exclusive

and potential benefits could be expected by establishing a common pattern of exercise so that all involved are familiar with the procedures and possible outcomes.

Table 2-5 Typical Rehabilitation Exercises

Exercise description	Objectives	Device	Ref
One-dimensional Applications			
Simple Movements	Varied isolated exercises reported	Slider, push-button, rotating handle	[79]
Driving VRE with force feedback	Single degree of freedom wheel with assistive force capability	Driver's steering wheel	[25]
Two-dimensional Applications			
VRE reaching tasks	Robot assisted movement training	MIT-MANUS 2-D robotic device	[86]
Simulated ADLs	Bimanual training – object movement and squeezing	Wrist flexion and transport device	[87]
Reaching tasks with weighted styli	Bimanual movement control	Mechanical stylus and sensors	[88]
Reaching tasks	Assessing EMG activity during joint isolated movement and corresponding angle, velocity and interaction torques	Air skate and light targets	[83]
VRE reaching tasks	Wrist and arm assessment measuring volitional movements	Bespoke 1, 2 DoF robotic devices	[89]
VRE reaching tasks	Target reaching with augmented feedback	Music interface; rhythmic auditory cueing	[21]
VRE reaching tasks	Line tracing with EMG measurements	Digitizing tablet and PC screen	[90]
Three-dimensional Applications			
VRE gameplay	Individualised brain training for rehabilitation post-stroke	Camera tracked arm movements	[9]
VRE reaching tasks with force feedback	Robot assisted movement training	ARM Guide device MIME robot device	[14, 23]
VRE reaching tasks with force feedback	Robot assisted motivational therapy	GENTLE/S using FCS Haptic Master	[48]
Reaching tasks with stylus	Games: assorted reaching tasks, NHPT movement assessment	Phantom® Omni™ haptic stylus	[82, 91]
Reaching tasks with force feedback	Robot assisted movement training	ARM Guide robotic device	[92]
Flight simulation VRE	Multiple haptic interfaces to assess coordination, etc, and tele-rehabilitation	Rutgers Master Glove (RMII) and Rutgers Ankle	[93]

Table 2-5 indicates the types of exercises/activities that have been used with rehabilitation devices designed for use with, or applications involving, the upper limb. This is not exhaustive and is intended to illustrate the types of common exercises or activities used in

both simple and sophisticated devices. The exercises are grouped around activities involving movement in straight lines (1-D rare but possible) or constrained about a single axis, within planes (2-D: typical of PC interaction) or within volumes (3-D: most common everyday activities). Whilst some activities are arguably artificial (1-D task), they can and do contribute to the experience and activity in a typical environment so may be considered as valuable building blocks for more complex tasks.

The proposed ARMaT device will be a 2-D desktop based activity, typical of computer mouse interactions with a simple VRE, and hence familiar to most users. The system will be a kinematic measuring device although there is inevitably some dynamic interaction given the weight and friction forces inherent in such reaching tasks. The devices/systems indicated in Table 2-5 are included to indicate that the proposed ARMaT device has direct relevance to the work by others and is hence valid as a useful measure of rehabilitation.

2.4.6 Quantitative Outcome Measures

The use of outcome measures to attempt to quantify the effects of physiotherapy is well established [94]. There are a large number of measures available but each one has its own particular application and peculiarities of use. The choice of tool or instrument to use is rarely well documented and relies heavily on the advice of colleagues or requirements of an organisation. Some measurement tools are easier and quicker to use than others and some may be free whilst others require payment and/or additional apparatus and/or training. A number of factors affect the choice of measurement tool, not all of which are related to selecting the most appropriate one for the patient at any one time. As noted in chapter 1, different scales may or may not adequately track progress along a significant portion of the continuum of ability.

Most scales are specific to conditions or desired outcomes. As no ARMaT tool currently exists for the upper limb, the most appropriate existing tools will be used to quantify and/or compare any proposed exercise with normal PT/OT activities. It is unlikely that this will result in the most appropriate baseline for assessing the benefits of an ARMaT system but, a baseline is needed in order to establish the credibility of any new therapy.

The Chartered Society of Physiotherapy produced a valuable guidance document for its members [94]. This document identifies over 200 clinical scales or measurement systems which cover all aspects of PT practice. The document lists a number of key criteria in selecting an outcome measure and these are summarised below:

- Appropriateness – is it relevant to the user's problems and the intervention?
- Internal consistency (equivalence) – how well a scale measures aspects of a single attribute
- Reproducibility (stability) – does the measure yield the same result on repeated occasions where no change is present
- Inter-rater and intra-rater reliability – does the measure yield the same result on different occasions when administered by different people or when used by the same person at different times?
- Validity – the extent to which the measure records what it is supposed to record

- Responsiveness – the ability to detect small but significant changes that reflect a patient's actual progress.
- Interpretability – can a range and limits be established against which meaningful measurements can be made?
- Acceptability – is the assessment sensitive to the culture and ability of users?
- Feasibility – can the measure be carried out readily and does it require any special training?

Clearly any measure that is essentially qualitative must be used in context and under similar conditions of measurement, experience of therapist, therapist training, etc, and must reflect the condition and abilities of the patient.

In an attempt to understand the most commonly used clinical scales and measurement technology used in neurological rehabilitation van Wijck [27] sent over 2,500 questionnaires to members of the World Forum for Neurological Rehabilitation, distributed over 75 countries. Only 68 were returned and most of these indicated that only a few clinical scales were used. There was limited use of more than one scale and concerns were raised over the available resources and training to use more scales more effectively.

Of the 42 scales identified by the respondents, the three most popular were:

- (Modified) Ashworth Scale
- Functional Independence Measure (FIM)
- Fugl-Meyer (FM)

These scales are commonly reported in the literature and appear to have become the gold standards by which a variety of other assessments or therapies are measured.

More specific to CP, Boyd *et al.* [80] reviewed 48 studies on the management of upper limb dysfunction in children with CP. Among their detailed considerations they observed (p153) that there was a:

> *"paucity of evidence for most treatment approaches for upper limb dysfunction in children with CP", and that "many upper limb studies have restricted the measurement of out-come to impairment variables such as spasticity, muscle length or joint range of motion."*

The conclusions of these surveys might suggest that many assessments are extremely valuable but subject to a number of issues. Correct selection is not always obvious and may be influenced by the amount of equipment required to make the assessment, such as noted for the Melbourne Assessments [95]. Also, uncontrollable variations both within the assessment and between assessments can lead to lack confidence in the findings and potentially support for further investigations. Such variations might be considered normal for these assessments but they may also be considered as clear indicators that an improved assessment is still required.

2.4.7 Minimising Measurement Variability

It is impossible to account for multiple variations in experiments with individual patients but, potential effects may be accommodated or isolated by adapting the experiment to the individual. The basis for all measurements must be one of relative progress from an initial state to a final state with some form of reference to a desired outcome. There is an implied agreement that the space between these two states is a continuum of relative ability rather than conformance with a known standard.

Movements may be influenced or even defined by one or more of the following factors, either working in harmony or opposition or some undefined state between:

- Body segment size – activities must be reachable
- Physical strength – activities must be possible
- Required dexterity – activities must be achievable
- Flexibility and suppleness - activities must be achievable
- Existing physical disabilities – activities must be appropriate
- Required range of movement - activities must be possible
- Physical limits of environment – location must be appropriate
- Complexity of task – progression must be possible and predictable
- Familiarity of task – related to ADL or readily trained
- Value of task – patient valued tasks
- Emotional state – calm and accepting, preferably enthused
- Emotional surroundings – prepared for therapy with supportive carers
- Mental disabilities – assessed for influence

Exercising the upper limbs may well hold the key to assisting broader sensorimotor recovery and possibly other higher functions following ABI. If the objective of recovery is to permit the patient to live an independent and dignified life then it seems logical to do this by using natural movements during their treatment. This is what PTs and OTs do, for the most part, so this approach would be logical in the development of ARMaT devices.

2.5 Measuring Human Performance

Well established systems of measurement and assessment exist for every manufactured product in the world. Established standards exist for new products by which their current performance and potential development can be assessed. However, standardised and transferrable quantitative measurement and assessment of human performance continues to be developed. There are standards of assessment of normal human physical behaviour (beyond basic anthropometric data) but only limited standards for assessing special behaviours such as rehabilitation from an injury or chronic condition. The hundreds of qualitative scales [94] available cannot be realistically combined to provide a common and reliable starting point for quantitative measurements and no such measure or scale has been found in the literature.

> **"The only man who behaved sensibly was my tailor; he took my measurement anew every time he saw me, while all the rest went on with their old measurements and expected them to fit me."**
>
> **George Bernard Shaw quotes 1856-1950**

There is encouraging progress into making ART assessments responsive to a user's progress as attempted by Colombo *et al.* [10] who used an assistive device and scaled exercises. They developed an algorithm (p283) by *"hypothesizing and verifying the presence of a specific recovery strategy during the course of treatment".* This feature of their device *"actively changes the task and some related features or the type of assistance to increase the difficulty level of the motor task"* based upon mean velocity improvements in preceding tasks. A related approach had been used by Krebs *et al.* [96] with MIT-Manus although their algorithm did not actively change the tasks/features.

In order to explore the hypothesis proposed in chapter 1 the author attempted to develop an ARMaT device which provided an interactive data acquisition tool that has the potential to quantify rehabilitation in the upper limb. To make the device widely accessible, it was intended to be a desk-based, affordable system, preferably using readily available components with a minimum of specialist hardware or software. The device is intended to be an ARMaT solution rather than an ART device and was not intended to replicate the sophistication of rehabilitation robots.

Systems using rehabilitation robots represent the state-of-art in ART devices and many already exist in the research field, such as those noted in Table 2-5. Some of these devices, or their derivative, are entering commercial production. Perhaps the most developed of these is the InMotion ARM™ offered by Interaction Motion Technologies which was based upon the success of the MIT-MANUS devices. Whilst demonstrably effective, the cost and operational requirements are currently prohibitive to most patients and to some health care providers. This *"gym-of-robots"* (InMotion ARM™ webpage accessed 17/11/2014) is clearly a sophisticated and highly developed device but it requires a minimum working space of 1.4 m x 2.0 m x 1.2 m high, plus a chair. With a mass of 271 kg and electrical power connection of 1250VA it represents a significant piece of equipment, most suited for continuous use in hospitals and clinics. The operational cost of this device is reported by Wagner *et al.* [15] in their paper which demonstrated the financial viability of this device for clinics when compared with

traditional therapy. A capital cost of $230,750 (March 2011) plus an annual maintenance contract of $15,000 makes the device financially viable for centralised rehabilitation but unlikely to be installed in domestic settings. Hence there is potential for smaller/cheaper ART and ARMaT devices to address home-based assessment and therapy. Provided that the benefits of any device are evident, even low cost devices will not gain acceptance if they are not demonstrably valuable to the users.

As noted by Barry [97] (p1), work in PT is increasingly accountable:

> *"Families are sophisticated customers…Physical therapists are under pressure to keep current,…are accountable not only to patients and clients and their families, but also to third-party payers… we must justify what we do by demonstrating the effectiveness of our interventions…"*

The National Centre for Medical Rehabilitation Research (NCMRR) model, noted by Barry, identifies five domains of analysis and these are typically shown as a pentagon to indicate collateral effect rather than linear progression from one to the other. This has been compared by various researchers with the Nagi model [98]and World Health Organisation (WHO) [99] model which attempts to address the multi-faceted issues of disability and hence measures of improvement or progression of a disease. Irrespective of semantics, the intention is clear in that health and disability must be considered holistically. The treatment of one facet may dramatically affect other issues, or the perception of those issues, which in turn can alter the wellbeing and quality of life of a person, whether that be perceived or quantifiable. A useful diagram describing this inter-relationship is shown in Figure 2-8 [98].

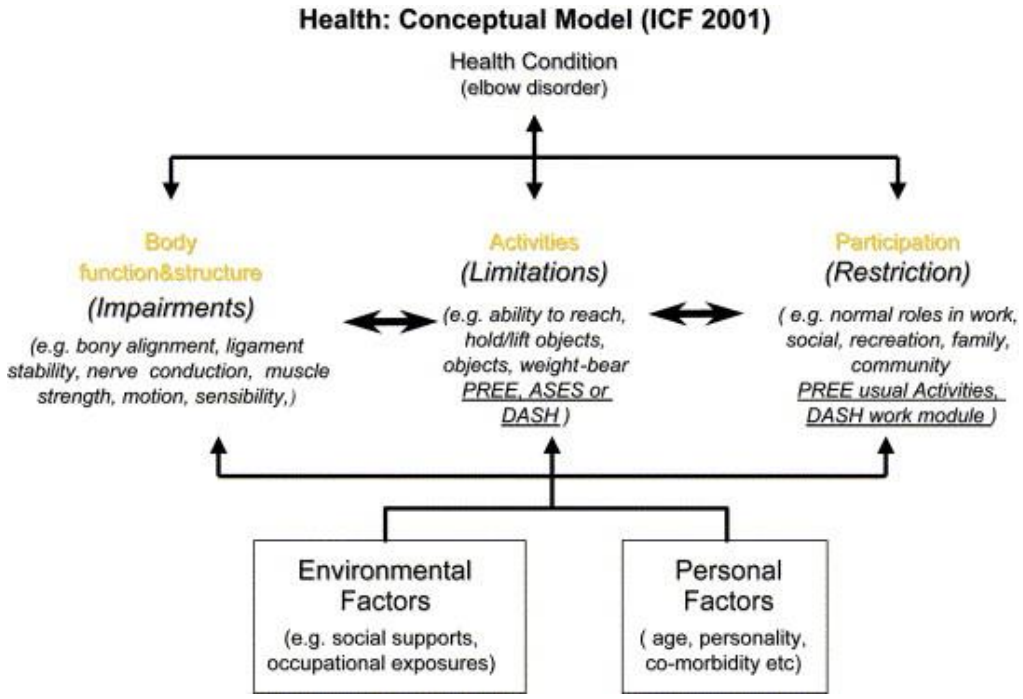


Figure 2-8 International Classification of Function (ICF)

Evidence of value is generally required to support a particular treatment or expenditure within healthcare institutions, just as investment in new machinery needs to be justified in

manufacturing or testing products. Clinical trials are now mandatory in most countries to avoid or limit the considerable harm that has been historically observed in non-trialled delivery of pharmaceuticals. More recently, the real efficacy of drugs and other treatments has been questioned as the demands on, and consequential costs of, health care continue to rise. On a more personal level, it is valuable for patients, carers and clinicians to know that the treatment is effective with minimal side effects and that the best treatment for a given condition has been chosen. In fact, evidence-based medicine is not a new concept and its use and validity [100] has been discussed for some time.

Typically, trials for established therapies have not been retrospectively required nor have extensions to existing therapies where they are essentially no more significant than the original. However, there is a general reluctance to accept new therapies as their effectiveness has not been assessed. How they might be assessed is the subject of evidenced based practice and guidance can be found from clinical epidemiology [101]. Notwithstanding the sensible recommendations provided by Sackett [100] who advises (p71) that: *"Evidence based medicine is the conscientious, explicit, and judicious use of current best evidence in making decisions about the care of individual patients"*, it is important to note that he also refers to rigorous trials where the placebo control group have "exhibited more favourable outcomes".

2.5.1 Evidence Based Decisions

There are strong arguments for evidence-based medicine (EBM) and related activities in the treatment of ABI. The level at which this is achieved can often be limited by resources, time, cost and other factors but the merit of strong evidence to support decision making is difficult to argue with. In order to grade the strength or reliability of evidence, Sackett [101] proposed guidance as to the levels of evidence that any investigation or trial might produce and these are presented in Figure 2-9 [100].

Level of evidence	Grade
Level I: Large randomized trial with clear-cut results (and low risk of error)	A: Supported by at least one Level I randomized trial
Level II: Small randomized trials with uncertain results (and moderate to high risk of error)	B: Supported by at least one Level II randomized trial.
Level III: Nonrandomized, contemporaneous controls	C: Supported only by Level III, IV, or V evidence
Level IV: Nonrandomized, historical controls	
Level V: No controls, case series only	

Figure 2-9 Criteria to Decide Levels of Evidence

The strength of evidence was investigated by Lannin and McCluskey [102] in their comprehensive review of previous studies. Of the 333 references identified for their review into *"rehabilitation for adults with traumatic brain injury"* only six were deemed to be of sufficient quality to assess further. They concluded (p245) that:

> *"There is still insufficient evidence to either support or refute the effectiveness of any one specific rehabilitation intervention to improve upper limb motor function*

in adults following TBI. There is a need for studies which investigate the effect of motor training interventions on upper limb outcomes in a TBI-only population."

And of the three RCTs that did pass their selection criteria they further commented that such trials should:

"also use consistent therapy protocols and outcome measures. Such trials should include a no-therapy condition or group (i.e., a true control group) so that interventions not involving motor training do not confound results."

Clearly, for a new ARMaT device to be seen as credible it must offer a high level of evidence of validity and hence professional acceptance. Similarly, a common and quantifiable outcome measure is obviously needed. For the trials noted in chapter 5 only limited participants were available and those were accessed as part of separate trial which was not under the author's control. However, for the future work with prototype 2 it is expected to provide Level II Grade B evidence according to Sackett's classification.

Having established the need to measure beneficial changes, any ARMaT device must be able to guide and monitor a series of realistic exercises. These will be most beneficial if repeated and adapted appropriately to the patient's changing needs. Ideally, they should be attractive and stimulating to the patients, non-trivial and meaningful to ADLs, and perhaps entertaining and motivational.

In order for the results to be fed back to the patients and their carers, and to inform the clinicians about further treatment, the results must be readily interpreted and presented consistently.

Good engineering and scientific practice can be used to determine the relevance and value of an exercise. Whilst medical trials are necessarily rigorous, the measurands are not always easy to identify or contain, being highly dependent upon variability in the patient group and within the intervention itself. Few measures, such as ability to carry out ADLs, share a common baseline as they have been developed for specific applications and occasionally are correlated to ADLs. Engineering measurements can be made which are repeatable, traceable, believable and transferable. This leaves the variability of the patients. Finding the right measurements to support rehabilitation in a diverse user group is the main challenge of this project.

It is fundamental to the success of any experiment or test that the conditions of the test and the test itself do not unduly influence the results being sought. In the context of ARMaT, this can be as basic as ensuring that the user or patient is comfortably seated and aware of the test, such as picking up objects or playing a board game. At its most simple, the object of the test might be to recognise and move a coloured object under the direction of a therapist. More complex issues arise when smaller details are being sought, or a deeper understanding of the effects of an injury or condition is needed. For example, can the user differentiate between shape, colour, position of nearest object and time to effect the movement? Can they successfully select the correct objects if they are moving or changing form, or if contrast and illumination alter, as is often present in computer games?

How a patient or healthy subject interacts with any interface depends largely on their perception of the environment that they are interacting with, whether it contains visual, audio,

tactile, movement or other stimuli or a combination of stimuli. Subjects without ABI or other conditions can generally be said to have a normal response even to complex environments. Although normal there would still be measurable variation, but the range might be relatively narrow and largely predictable. Patients with ABI may have a significantly distorted view of the world despite showing encouraging signs of improvement. They might demonstrate seemingly normal perception when measured in repetitive and simplistic tests of cognition although the range may be far wider than that for healthy subjects. When the environment becomes more challenging, the responses may become so variable that no pattern or categorisation is possible.

2.5.2 Measures of Normality

In designing any rehabilitation system or device the main objective might be to help users recover or acquire normal responses to normal stimuli. These might be measured against established psychological or physical tests or against new tests on normal users to establish baselines. But, what is normal? As noted in section 2.3 and demonstrated by Figure 2-10 [103], even normal capabilities can be tricked or confused by forcing them from their normal learned view of the world.

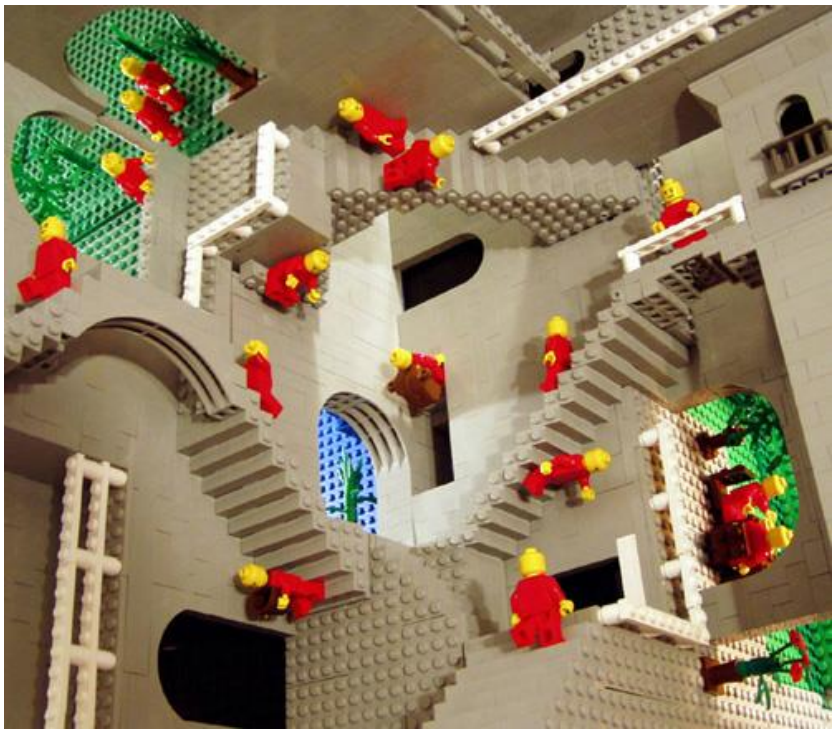


Figure 2-10 Representation of Escher's Drawings

No two people can really be determined as being normal in anything other than a simple assessment of a single function, and then only within statistical limits. normal vision has been established based on average capability to read different sizes of letters and numbers at set distances. It does not establish a good standard, just a standard from which minima for activities such as driving can be extracted.

The ability to see an object is taken for granted given normal or corrected vision. However, most people are aware of various visual anomalies that exist due to the construction and

functioning of the eye itself and with age or surroundings. If these factors are combined with the highly variable and largely unquantifiable behaviour of the neural messages that pass from the eyes to the brain then the potential for making perceptual errors and hence motor errors can be quite large. If any part of the eye, spinal cord or brain is damaged then this potential for error becomes significant and possibly dominant. Clearly, a simple pre-test procedure for operating within a visual environment must be that the patient can actually see what is being presented to them in a way that is meaningful to the intended test or treatment. They should be able to see sufficient detail and discriminate between objects in order to make the correct decisions and hence initiate the appropriate actions. Even the most able user might fail a test that they could not see properly or in the way that it was designed to be used.

If healthy subjects can be tricked or confused, either deliberately or inadvertently, then environments for patient subjects need to be developed with extreme care. They should not rely upon an assumption of "normal" behaviour to establish new baselines or to reconfirm existing tests. Typically, the literature reviewed for PT/OT and ART assumes ability and compatibility of the subject with the test rather than stating the appropriateness of the test to the subject. It is possible that the statistics used to present the data filter out participants with notable conditions such as poor depth perception or colour blindness; they could not progress because they could not "see" properly. The test or therapy is not addressing the needs of that subject. Instead they are effectively ignoring them because they do not fit with the "norms" for that highly variable group. Much will be lost by this approach and may already be distorting the results and subsequent recommendations.

2.5.3 Factors Affecting Human Performance

There are a number of assessment measures in use which attempt to classify or quantify a patient's current ability and then to chart progress [94]. Some of these are capable of quite fine division of ability whilst others are merely gross indicators. Each system of measurement was, presumably, developed for a specific assessment and probably works well within the often narrow confines of the original intent. Given the wide variety of conditions that affect sensorimotor capability, and the numerous complications that exist or arise due to that original condition, it is not surprising that multiple assessments have been developed, and may be needed by a therapist, to describe a patient's state. Many of these systems rely on unquantifiable statements to make an assessment. Additionally, some of these are either not graded or are impossible to grade. Combined with variable training in the use of the systems and tools, the result is a wide variety of uncorrelated and non-standardised "measurements" which cannot be compiled or manipulated to provide a cohesive or comprehensive assessment.

Typically, considerable time and resources are required to make any assessment and these compound the problems faced by PTs and OTs in providing useful, quantifiable and reliable feedback to patients, carers and clinicians. Following her investigations into the patterns of instrument use, van Wijck [27] (p23) states:

> *"More resources and education are required to support a more routine application of assessment tools and to integrate measurement technology further into neurological rehabilitation to assist in the process of quantification of outcomes."*

In any complex environment, the ability to standardise some measurements and make these objective and quantifiable is an advantage. By reducing the variability of input and measurement, any data obtained is easier to classify and isolate and hence is more reliable as a measurand, and as an indicator of potential benefits. The type of data that might be useful to record during a therapy session is not well documented. It is not known what data or sets of data are needed to adequately evaluate a therapy session and the user/patients response to that therapy. Hence, further investigation is required to inform what measurements may provide the most value and what effect they might have on performance in a therapy session.

It is possible to measure a wide range of mechanical and electrical signals that either directly measure a user interaction - movement, force input or speed - or indirectly measure a user response - work done or time taken. It is possible to measure too many factors and equally possible to measure too few, or to consider some factors as unimportant without any basis for this assumption.

It is not evident in the literature reviewed that even basic physiological factors were measured for users during either experimental evaluations or clinical trials. One exception was noted [46] where blood pressure and heart rate were recorded before, during and after a session involving prolonged walking on a treadmill, presumably as a safety precaution for the participant. The only other record in more than 150 relevant papers was on ensuring adequate or corrected eyesight [59]. Perhaps basic physiological factors are normally discounted as irrelevant, but common indicators of health such body temperature, pulse rate, blood pressure and blood oxygen are easily taken before, during and after sessions. They may hold a key message or part of a message that might provide greater understanding of the mechanisms of recovery. If this is true, then measuring as many factors as possible and deciding that they are or are not useful is advisable. If they are not useful, this should be identified and their contribution discounted.

The physiological factors in Table 2-6 are commonly recorded by clinicians to establish any significant indication of ill health or change in physiological function. Some are direct indicators of temporary conditions (saliva cortisol levels indicating stress levels) or they may be assessed and recorded for reference purposes. They are not complete indicators of health or ill health. Similarly, significant changes in one measurement do not always suggest correlated effects with another. They are however, readily measurable, non-invasive, reasonably reproducible for a given set of conditions, and may well be informative.

Assuming that a wide range of measurements were taken before during and after a therapy session, what value can this data add to the assessment of results? Clearly, some aspects such as body weight are not going to change during a session but may well alter between sessions. Other factors can be strongly influenced by levels of stress, eating, activity, etc, so will need to be treated with caution when large changes are observed. However, what if one of these normal changes shows a correlation with sensorimotor function, either improved or degraded, during a therapy session or between sessions? Can useful data or patterns be extracted from this? At present there does not appear to be any comprehensive evidence, based on rigorous measurement, to either support or dismiss any such hypothesis. For this reason, maintaining as many basic measurements as possible for users and patients may establish or dismiss any possible relationships, which may affect the success of the therapy.

Table 2-6 Summary of Readily Measured Physiological Factors				
Physical Measurement	**Method of Assessment/Device**	**Units**	**Normal range (adult)**	**Reference or Comment**
Blood Pressure (BP)	Digital gauge, sphygmo-manometer	mmHg	Less than 120/80	[104]
Blood oxygen - % haemoglobin saturated with oxygen	Oximeter	SpO_2	>95	[105]
Pulse	Pulse count	bpm	60-100	[106]
Muscle activity	EMG	mV	variable	[107]
Body temperature	Thermometer	◦C	37	[108]
Heart rhythm	ECG	mV	variable	[107]
Forced expiratory volume in one second ($FEV_{1);}$ Forced vital capacity (FVC)	Spirometer	l	Age related	[109]
Peak flow (PEFR)	Peak flow meter	l/min	600 (men) 400 (women)	[110]
Blood glucose	Glucometer	mmol/l	3.5–5.1 (before meals)	[111]
Eye sight	Snellen test	ratio	3/6 to 6/6	See section 2.6.1
Hearing	Audiogram	dB	-10 to 20	[112]
Stress	Saliva cortisol	nmol/l	80–600	[113]
Body Mass Index (BMI)	Scales/height chart	kg	17-24 (children)	[114]

There are a number of medical conditions and degrees of that condition that are normally indicated with similar measurements. Obvious extremes are conditions such as chronic obstructive pulmonary disorders (COPD) where reduced airflow results in reduced oxygenation of the blood and can lead to significant reduction in mental and physical capacity. These symptoms are well documented in otherwise healthy pilots who fly without supplemental oxygen at altitudes above 12,000 ft, whilst some people can be affected as low as 8,000 ft. The resulting condition of hypoxia (reduced oxygen) seriously affects pilot judgement without their being aware of any loss of ability. Another common example is diabetes, where the body fails to regulate the absorption and use of sugar. In extreme cases, the patient can die but normal fluctuations can result in considerable confusion, loss of coordination and reduced muscle power. Normal healthy people can regulate their blood sugar within normal limits for them but, patients with complex conditions, possibly combined with old age and erratic diet may experience swings of blood sugar with attendant symptoms.

Table 2-7 shows some common conditions and their symptoms as related to the typical health indicators noted in Table 2-6.

Table 2-7 Selected Conditions with Potential to Affect Therapy Outcomes

Measurement	Condition and symptoms	Reference
Blood Pressure	Elevated BP may cause: excessive tiredness, confusion, visual changes. Low BP may cause: light-headedness, unsteadiness, blurred vision, confusion and general weakness.	[115]
Blood oxygen	Reduced SpO2 can cause: reduced attention span, muscle fatigue, impaired short-term memory, difficulty making decisions, impaired hand-eye coordination.	[116]
Pulse	Elevated pulse may indicate: stress and anxiety.	[106]
Body temperature	Elevated body temperature may cause: increase in error rates, unreliable short-term memory, perceptual and motor skills slow, and reduction in capacity to perform tasks.	[117]

Earlier, the effect of the user's surrounding environment was questioned. Table 2-8 lists a number of environmental conditions that might affect a user during therapy and Table 2-9 shows the primary effects of exceeding normal limits. As with the physiological factors noted above, the effects have not been recorded or even indicated that they have been measured in any of the literature reviewed. The purpose here is to question if the various factors might have an influence on assessments and attempt to see if a pattern of response might be predicted.

Table 2-8 Environmental Factors Affecting Therapy Measurements

Environmental Measurement	Instrument	Units	Normal acceptable range	Reference
Ambient Temperature	Thermometer	^{o}C	16 -25 (typical indoor conditions for the UK)	[118]
Ambient Humidity	Hygrometer	% RH	40-80 (typical indoor conditions for the UK)	
Ambient Pressure	Barometer	1.01 Barg		
Ambient noise levels	Sound pressure meter	SPL (dBA)	NR 30-50	
Air Quality	CO meter CO_2 meter	ppm	350-450 max 600	
Ambient light levels	Lux meter	Lux	10 – 100,000	

Motivation is a typical psychological factor in the context of providing an enjoyable or tolerable experienced with an ARMaT system. There is growing interest in assessing the value of motivation in rehabilitation [21, 48] as it may promote recovery through a variety of mechanisms, not least of which are engagement and repetition.

Table 2-9 Physiological Effect of Exceeding Environmental Norms		
Environmental Factor	**Known Physiological effect**	**Reference**
Ambient Temperature	Below 16ºC normally clothed, inactive people may become chilled and respond more slowly. Above 25°C people may be come lethargic and confused, particularly when exercising.	[118]
Ambient Humidity	Discomfort and excessive perspiration causing distraction and lethargy	
Ambient Pressure	Usually related to weather conditions; exacerbate temperature and humidity effects.	
Ambient noise levels	Distraction or irritation; typically frequency dependent	
Ambient light levels	Below a certain level vision limited to monochromatic and even above this acuity may limited	
Air Quality	Thought to contribute to "sick building syndrome"	

In sports injuries, where the desire to recover professional performance is highly valued this is an obvious conclusion. However, similar motivation can be found to support recovery from acute and chronic injuries to facilitate even modest ADLs. It would be reasonable to expect a well-motivated person to do well at a task and for a poorly motivated person to do less well, despite appearing to be equally capable physically.

It is predictable that activities which excite or enthuse people are well received, are readily accepted and practised even if physically or mentally challenging. Conversely, tasks that are perceived as boring, tedious or irrelevant seldom receive much attention. Rarely is motivation noted in the literature on automated therapy proposals despite the long-standing acceptance of the Yerkes-Dodson Law [119] which established a direct link between motivation and learning in 1908. Of interest is the range of this motivation, as noted (p481) by Yerkes and Dodson:

> *"an easily acquired habit, that is one which does not demand difficult sense of discriminations or complex associations, may be readily formed under strong stimulation, whereas a difficult habit may be acquired readily only under relatively weak stimulation".*

This is notable in military instruction where basic tasks are rapidly and robustly instilled whereas complex technical tasks are more gradually and less forcefully taught.

Why do some people re-learn ability and others do not? As an example, an older sedentary person with a paretic arm following stroke may be satisfied to have survived and grateful to have retained significant function. Supportive daily living aids can make life comfortable and independent. Perhaps the imperative and support to retrain a limb is therefore not significant and so little progress is made. Such assumptions can be transferred to others groups from infants to adults. Surviving a traumatic event and the relief of parents, partners and carers might overwhelm any imperative to recover limb/muscle function immediately following

trauma. Similarly, the recovery time for injured limbs or inactivity in a limb can be significant and it is possible that lack of ability is also learned during these unplanned and undesirable "training" sessions. If the brain has the potential to transfer sensorimotor function from damaged areas to healthy segments then inactivity can be learned just as readily as beneficial movement.

Motivation may be critical in assisting recovery and there is significant anecdotal evidence of this as well as structured research into the benefit of motivational environments within robot rehabilitation. Loureiro *et al.* [48] note that motivation enhances therapy and that environments which promote attention and motivation proved more effective in their work with stroke patients. They promote the idea that any rehabilitation environment should have visual, haptic, auditory and performance feedback. They advocate interesting but not too complex VREs and their initial findings suggest that less haptic force feedback is probably beneficial.

The effect of positive motivation on rehabilitation progress is not well documented, as controlled studies that isolate this are difficult to conduct for a number of reasons. Motivation will be very different for each subject so cannot be standardised or even readily classified. The motivation for an adult to recover so that they can drive, as used by Johnson *et al.* [25], is predictable and potentially very valuable during therapy, whereas a child's interest in sport or an immersive story [17] could be used to great effect for their therapy. However, neither of these is likely to motivate an older, sedentary person. The cost of long-duration therapy is substantial and most health care systems cannot afford to support subjects continuously in this way. The significant collateral care costs of not providing continuity of care are considerable [19] but these may be delayed or sourced from other financial budgets; hence masking real costs. Access to services may be limited by the circumstances of subjects and the carers. Even if the therapy were freely available, getting to and from a clinic whilst working and/or attending to other family needs may restrict many subjects from accessing services [120].

There is considerable difficulty in assessing and quantifying the more significant psychological factors such as depression, reaction to drugs, etc. Hence, these are excluded from this current research. However, these factors may influence any measurement as any significant psychological behaviour or response could dominate any interaction with an ARMaT device and VRE.

Given the potential to retain and develop functionality, it would appear essential that subjects should be assisted to recover as fully as possible. This is attempted during the acute care phase of most treatments. However, once the acute phase is over and some self-supporting independence is achieved, subjects are typically discharged and may receive only periodic therapy as out-patients. It is assumed that the subject and carers will continue therapy and will be sufficiently motivated to support themselves. This is not generally observed [19] amongst stroke outpatients and potentially other patients as well for the same reasons. The ability to continue rehabilitation and monitoring at home may provide long-term benefits to both patients and health care providers.

2.5.4 Mental Imagery

It was noted in section 2.4.3 that physical and imagined movement can evoke similar responses and that these can be observed using fMRI and other processes such as positron

emission tomography (PET) and transcranial magnetic stimulation (TMS). Jeannerod and Decety [121] (p731) summarised related studies and observe that there is "converging evidence for a similarity of neural processes involved in central representation of actions and motor imagery." They conclude that motor imagery can be used "*as a direct means of accessing the mechanisms of action preparation and imitation*". Their conclusions apply equally to normal subjects as those with motor impairments such as PD, hemiplegia and apraxia. The observed deficits in physical movements were also reflected in mental motor imagery. It might be suggested that in order to rehabilitate real movements, mental stimulation and exercise would also be required and beneficial.

In a development of earlier work Jeannerod and Frak [122] describe work with TMS and the resulting motor-evoked potential (MEP) in the upper limb for hemi-paretic patients imagining forearm flexion-extension. They concluded that (p738*)* "*motor imagery should reveal itself as a potent tool for probing and possibly improving the functioning of the motor system*" and that *"rehearsing effects observed during motor learning…..opens new possibilities for rehabilitating patients with motor impairments*". This area of work is relatively simple to adapt to basic reaching tasks and might usefully be employed in any ARMaT device applications. It would be interesting to note whether a simple task might be measurably improved by application of mental motor imagery. Provided that the ARMaT device were sufficiently sensitive, then such a device should be able to measure changes in ability as a direct result of mental imitation. Whilst this is interesting in itself, the main aim is to support rehabilitation and such a process may well add value to the potential therapeutic element of a very simple ARMaT device.

2.6 Virtual Reality

As with the real environment in which subjects use computers and interact with other devices, virtual realities can similarly affect their behaviour. Most games and game devices involve a person by engaging them in a rich audio-visual environment which they control using manual devices. Games are cleverly designed to transport the user into a virtual world where they may not need to think about the complex actions that they perform as they interact with the game whilst constantly responding to varied stimuli. Some games can include tactile and movement feedback using simple force feedback as in commercial joysticks or elaborate 3-D enhanced motion environment devices such as that shown in Figure 2-11 [123] which cost less than £8000.

A therapeutic environment may use game play to engage the patient as noted in Table 2-5 and the majority of these have been demonstrated to be of beneficial effect. Not all attempts at VREs are as well researched and many "casual ART" systems are emerging from game designers. Whilst movement and motivation are important, it is more important that the user is actively participating in the movements that they are making. They are involved in a process of measuring and/or advancing their own sensorimotor skills rather than defeating or interacting with an arbitrary game environment.

Figure 2-11 Self-contained Motion Platform

It is important to realise that most gaming environments deceive their players in order to accelerate the game's apparent speed or complexity. This is an enjoyable experience for healthy users but has questionable results for patients with specific sensorimotor issues or deficits. Whilst normal subjects may be able to transfer from a virtual world into their real world and back again, patients who are developing new basic motion skills may become distracted by the VRE if it does not conform to the reality of their daily lives. Indeed, Haptic representations of virtual objects which do not reflect real objects can be significantly more difficult to identify than representations of real objects [124], adding potential confusion and SCS feedback delays. This effect was also noted by Bowler *et al.* [91] in their work on real,

virtual and embedded NHPT assessments. They noted that the time to complete a similar task increased as the level of realism decreased, as did the variation in times about the means for each task. Similar time increases were noted by Chemuturi at al [125] in their work on adaptive training algorithms.

There is limited value in being extremely adept at beating a game when none of these skills transfer to the real world. There is a possibility that more attractive and significantly more repetitive and limited skills needed for gaming overwhelm those needed for life. If repetition and engagement are key to re-learning then inappropriate or sub-optimal movements may become permanent, resulting in potentially self-limiting behaviour and movement as noted in section 2.3.

Simple and unambiguous games have been used in reaching tasks such as the "fork model" devised by Loureiro *et al.* [13]. Similarly Kahn *et al.* [23] used a fan type target array of numbered targets on a black screen. They also included an additional target that was used to assess learning following training on the first five targets. This is not dissimilar to the calibration system used by Cameirão *et al.* [9] in their Spheroids game, although the spheroids game itself was more sophisticated.

Apart from moving a body segment or sensor there is some merit in performing a selection task by pressing a button or other action. This may introduce additional complexities that are not useful to assessing upper limb movement. Such a limitation was noted by Langdon *et al.* [126] in their work on haptic force-channels and attractive-basins where the results from a number of tests were considered potentially invalid due to the patient's inability to click a button. Their area of interest was the potential for speed improvements in selecting targets using a simple force feedback joystick, which showed promise. However, the results were potentially marred by this simple limitation that normal users would take for granted.

In order to understand what may be distracting or ambiguous to a user, typical sensory abilities should be assessed and a limited review of these are presented in the following sections. The typical limits from these reviews provide design guidance for subsequent development of any VRE and related hardware.

2.6.1 Human Sensory Limitations

The dominant sense for computer interfaces is vision, the ability to see real and virtual objects, which is taken for granted by most people with normal or corrected vision. If any part of the eye or CNS is damaged then then the potential for making perceptual errors, and hence motor errors, could be significant and possibly dominant. One such condition is Anton's Syndrome which may result from a CVA. The patient is effectively blind because of brain damage to the occipital lobe and primary visual cortex, which is responsible for vision. However, the patient denies that they are blind, despite bumping into obvious objects, because the damage has extended into the visual association cortex. In essence, the patient is blind but the brain is so damaged that it cannot accept the loss of visual information and constructs images, often elaborate, presumably based upon experiences that are retained by the patient. When asked to describe what they see, patients may give detailed but completely inaccurate descriptions. This is an extreme condition but a less significant example of this would greatly undermine the value of any verbal reports from patients. A more subtle experience is "action-effect blindness" noted by Hamilton [26]. Here the participant may fail to identify a right-

pointing arrow whilst executing a right-hand motion. The assumption is that a common piece of SCS code is being utilised for both perception and action; one of these may then dominate.

If normal users can be tricked or confused, deliberately or inadvertently, then a VRE for patients with known or possible SCS deficits should be selected with extreme care. By understanding the basic limitations of the normal senses and how they help people to perceive their environment, unrealistic challenges in any ARMaT VRE environment can be avoided. Equally, where deficits are understood, a VRE might also be designed that can be adapted to meet potential deficits in patients and to address their changing conditions during recovery.

Vision

The primary sense for most people is vision, and typically stereoscopic vision allowing depth perception. Most motor skills are developed through visuo-motor feedback training from birth and these form a baseline for all further developments in motor skills.

The ability to see objects (from eating utensils to fast moving traffic) and to place these within the immediate and distant environment is obviously essential to most people. What is less obvious is that the ability for people to see themselves move or act is nearly as important. However, seeing oneself move need not be relied upon as much as might initially be expected, given the reliance on sight for most tasks. For a variety of reasons, sight is the dominant sense without which most tasks are made extremely difficult. Obviously, people can live without it but possessing it makes life so much easier and safer. The origins of normal visual capability predispose people to certain abilities and impose several limitations. Many of these facets of vision can be readily understood, and by avoiding the confusing or ambiguous messages that might result, building a VRE that minimises visual conflicts or confusion should be possible.

Whilst the construction and operation of the eye are fascinating, it is not necessary to understand the intricate workings of this specialised organ in order to understand how best to stimulate it and assist a patient using an ARMaT device. The following sections identify principal aspects of normal vision that could affect the results obtained from an ARMaT device that utilises a VRE.

The human eye sees by sensing light that has been either directly transmitted to the eye (looking at the sun or a computer screen) or reflected from objects (the sun's rays reflecting from a red ball in a green field). The most important consequence of vision is the recognition of objects in daily use so that they can be used effectively, or to avoid collisions. In order to do this the eye has evolved the ability to identify coloured light and the intensity of any light falling on its sensors. The eye has two sensor types, rods (about 100 million spread around the retina, except in the fovea) and cones (about 5 million mainly localised within the fovea), which provide the wide visual capability that most people enjoy. Rods are essentially light intensity sensors and cones are wavelength selectors.

The eye can sense a very limited range of the electromagnetic energy spectrum (from beyond Gamma rays at 10^{-12} m to radio waves exceeding 10^{3} m) which lies within the light spectrum of 10^{-9} m (ultra violet) to 10^{-3} m (infrared). Typically, this visible spectrum will include wavelengths between approximately 400 and 700 nm as indicated in Figure 2-12 [127]. Within the visible spectrum the eye is more sensitive to certain wavelengths than others, with a typical sensitivity peak at 550 nm determined by the selectivity of the rods shown in Figure 2-12 [127].

The colour selectivity of the cones is centred on the blue, green and red wavelengths and Figure 2-13 [127] indicates the approximate response of the eye. Where light intensity is in the range 10 to 10^7 cd/m^2 vision is said to be photopic. From 10^{-1} to 10^{-6} cd/m^2 vision is said to be scotopic and is dominated by data from the rods. A mixed or mesopic range exists around 1 cd/m^2 where cones and rods are similarly responsive. The distribution of rods around the retina is more uniform than the concentration of cones in the fovea. Hence, despite the increased number of rods, their distributed nature means that scotopic vision is less precise or defined than photopic vision.

If a VRE is to be interesting to use, it is important that it is designed to incorporate defined, well illuminated colours that an average user or patient, without damage to vision systems, can perceive accurately during repeated exposure. Similarly, the work area needs to be illuminated properly to permit the user to perceive the real and VRE in context. Some conditions such as colour-blindness may preclude the use of certain colours and a variety of colour schemes could be provided to ensure that basic recognition of the VRE is established.

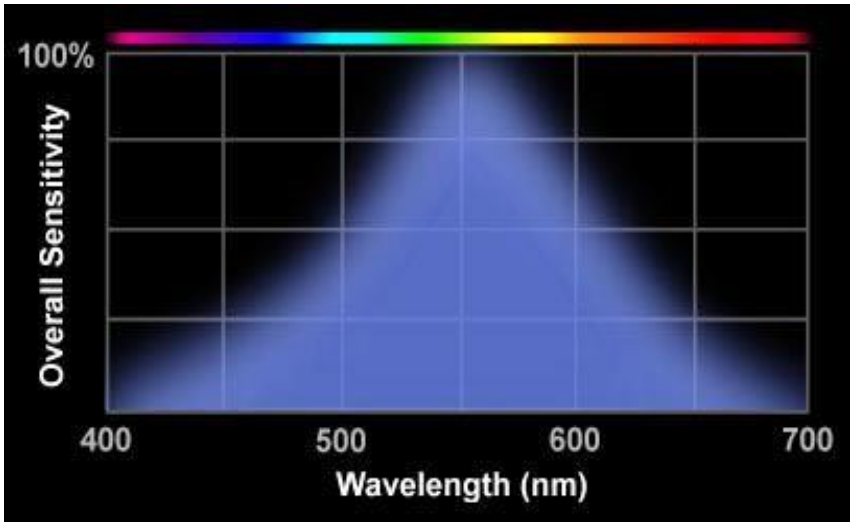


Figure 2-12 Spectral Sensitivity of Rods

One possible benefit of the use of different colour schemes might be in identifying abnormalities in colour or intensity perception and identifying areas of the brain that might have been affected to cause such abnormalities. However, this is beyond the current scope of this project.

Normal and Corrected Vision

In order for the retina to convey suitable information to the brain, the image that it receives needs to be meaningful to start with. This is a very basic requirement that can be tested in a number of ways. It is also a pre-requisite if the performance of a subject could be influenced by their responses to visual cues or signals. The minimum requirement is that they can see the work area adequately, if necessary by wearing corrective lenses.

Everyone has a blind spot caused by the absence of rods or cones in the area of the Optic Disk. This is where the axons of the retinal ganglion cells converge, forming the optic nerve. Interestingly, this blind spot does not appear as a dark area but is normally seen as white, the absence of photoreceptors being filled-in or completed by the brain. Vision in this limited

peripheral area is not possible and hence activities demanding fixation in one area whilst requiring awareness of adjacent areas, particularly at close distances, may well lead to discrepancies in the perception and use of any VRE. This effect is readily demonstrated by closing one eye and staring at a fixed point in a book at arm's length. Detail at the edge of the book will be lost. Using both eyes virtually eliminates the effect of the blind spot.

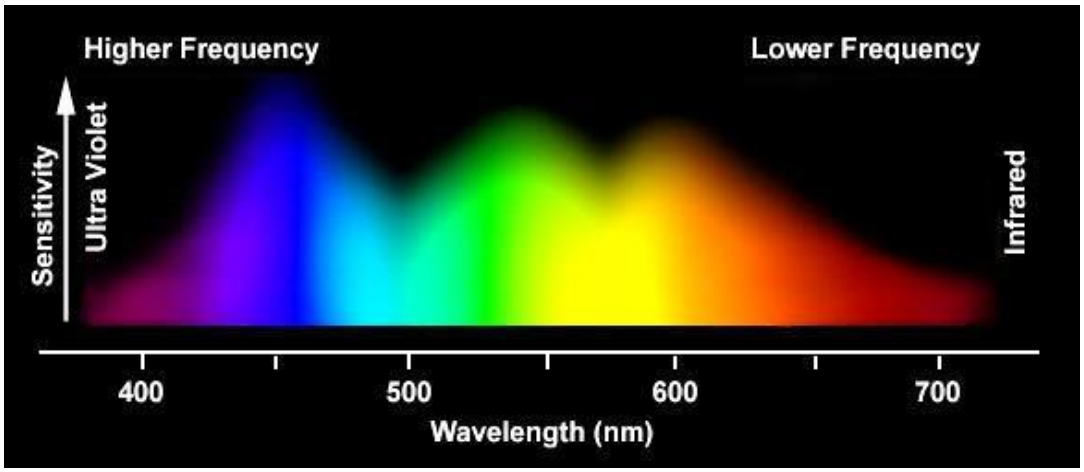


Figure 2-13 Colour sensitivity

The ability to identify an object at distance is used as a measure of visual acuity as noted in section 2.3. An average value was established by large scale testing of healthy subjects and sight test are compared with this. If a person can read the normal text size at 6 m then they have 6/6 (20/20) vision. If they can only read text that a normal person would read at 3 m then they have 3/6 (10/20) vision. They are potentially myopic. Generally, visual acuity degrades with age and is diminished by poor light. Some people may have normal acuity but will fail a standard test because of cognitive factors related to bunching or arrangement of otherwise readable letters. Cognitive function may also dramatically affect recognition as the Snellen test is an isolated test without context for the reader to place the letters as part of words that they can recognise.

Within a VRE ambiguity of context should be avoided and simple shapes rather than cognitively complex images should be used where the subject is expected to discriminate between areas or activities.

Angle of Vision

The normal brain interprets data from the eyes in a variety of ways. This activity takes place in the visual cortex and starts with cortical cells receiving information from the retinal cells via the optic nerve. Cortical cells respond best to gradients in the intensity of light conveyed to them. As such, they respond to light coming from edges and corners, borders and curves. They also exhibit a preference, called the Oblique Effect, to vertically or horizontally orientated lines and respond poorly to lines orientating at 45 degrees. This is illustrated in Figure 2-14 [128] where discrimination is degraded for lines drawn horizontally or vertically. At some point oblique lines will become indistinct whilst vertical lines remain discernible. This preference is not universal and some people (notably those with astigmatism) actually experience the reverse effect. However, for the majority of people the correct perception of an intended VRE can be maintained by working within this limitation and using vertically or horizontally orientated objects.

Movement, Intensity and Contrast

Whilst people perceive the world the right way up, it is actually sensed upside down due to the inverting nature of the lens. The brain interprets the inverted image data and corrects it without conscious thought. Similarly, some objects appear very different under various light conditions, at varied distances, if they are moving, if the observer is moving, and if they are compared with, or in the presence of other objects. The brain uses inverse optics to establish a usable description of objects based on raw data from patterns of light being sensed by the rods and cones of the eye.

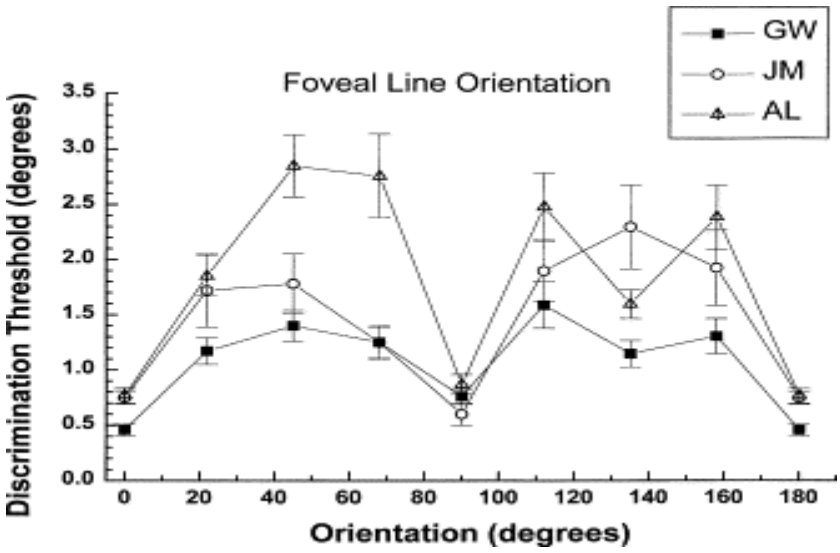


Figure 2-14 Oblique Effect: Variation between Subjects

The combination of the data from both eyes is carried out in binocular cells where the cell responds to the different data being received from each eye. There may be a preference for data from one eye, called ocular dominance, but these cells respond to binocular data streams. This ability provides the brain with information on the relative distance between objects which is essential in establishing a usable picture of real and virtual environments.

Despite the enormous amount of data received, the brain establishes patterns of understanding that make sense of the data that it has to process and hence interpret the images of the world that are needed. Simple rules are observed to simplify interpretation such as, light not passing from an object hidden behind a solid opaque wall and that similar sized objects appear smaller at distance than in close proximity. These rules are learned during an infant's exploration of the world and throughout healthy development and assist in completing both complex and simple tasks.

The contrast between object edges can result in misleading perceptions of a VRE. It can also be used to positive effect in defining areas of interest by using this contrasting accentuation. This was demonstrated by Ernst Mach, who used patterns such as that shown in Figure 2-15, recreated here by the author. Each strip is less intense by 10%, from black to white and each strip is uniformly coloured across its width and height. However, the appearance of the strips suggests a gradation of intensity of reflected light across the strips and band of darker or lighter colour between the strips known as Mach Bands. These bands do not exist and are a perceptual consequence of the neural processing of retinal information that can lead to misleading results.

A similar pattern is shown in Figure 2-16 where a centre dot of common intensity is surrounded by rings with different intensities. This shows that the dots are perceived as different lightness despite being identical based on the contrast of the surrounding rings. This effect is obvious in these examples but could be misleading in a VRE where several objects are present and decisions need to be made on which one to select, the furthest one or the

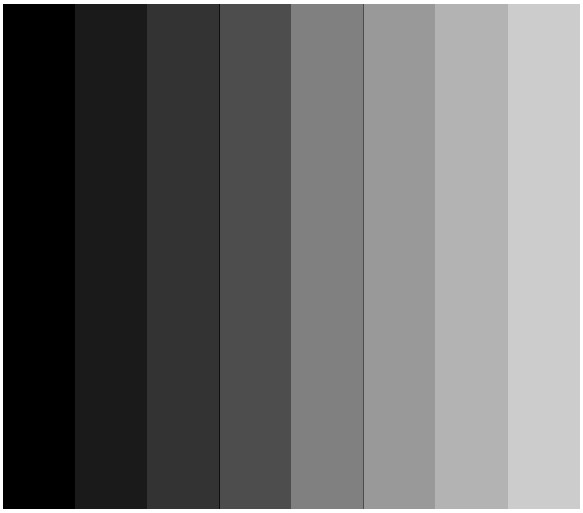


Figure 2-15 Mach Bands showing perceptual errors in strips of uniform intensity

darkest one. It is notable that contrast sensitivity changes with age resulting in a required contrast at 60 years old which is twice that required by a at 20 year old subject. This increases to a contrast of six times by the age of 80 [129].

Basic Detection and Discrimination

In order for people to interact successfully with their surroundings, they must be able to detect objects within the general environment, discriminate between the desired object and other similar shaped objects and finally to identify specific details on the object to refine the selection process. In healthy subjects, this all happens without conscious thought but the

process relies on specific information, and the depth of information increases with the amount of detail needed to select the correct object.

Figure 2-16 Lightness contrast demonstrated for dots of common intensity

Assuming adequate visual acuity, objects are normally detected based on their form or shape and artists have used this simple informational structure to guide viewers through their paintings for thousands of years. Typically the edges of objects are detected where the contrast is most apparent and tests have been developed which assess the ability to detect shapes based on the fundamental neurological data that the brain processes[130]. There are also differing requirements for scotopic, mesopic and photopic vision. In very low light conditions, even large objects are difficult to see. As the light level increases, more detail becomes apparent and both large and small objects can be determined.

Even if a new object is not immediately recognised, a simple structure such as a circle or square shape within it can usually be recognised. In order to construct a working image people build components together to create whole images that can then be recognised as familiar objects. Any VRE needs to address these basic considerations and potential limitations.

2.6.2 Summary of Vision Considerations

If a VRE is to be usable it is essential that either the user be assessed to ensure that they can see the work area properly or the VRE is designed to incorporate images that correspond to any potential limitations in the users' vision. Ideally, all users should be assessed and corrective lenses worn, if necessary. Non-permanent conditions such as strained eyes and anomalous myopia (where the eye rests at a neutral focal point due to lack of stimulus) should be addressed by sufficient rest and relaxation between sessions and adequate illumination and active visual involvement during sessions. A summary of the most significant issues associated with a VRE are contained in Table 2-10.

Table 2-10 Recommendations for Visual VRE			
Visual Aspect	**Recommendations**	**Limitations**	**Remarks**
Wavelength	Use clear strong colours; simple red, green, blue imagery at basic levels; more complex colours at higher levels but maintain differentiators; provide alternative colour schemes to respond to lack of perception.	Colour blindness, damage to occipital lobe and/or visual cortex; vision syndromes	Difficult to assess vision defects at early stages of recovery; use common objects to determine if user can perceive VRE effectively
Intensity	Good illumination and contrast; ambient at 200-400 lux; VRE images should be well-defined and contrasting with VRE background.	Older people have a lower sensitivity due to varied factors	Provide for variable intensity settings and benchmarks for visibility of VRE
Normal and Corrected Vision	Ensure that users can see the work area properly using standard tests and corrective lenses if necessary. Check periodically.	Some conditions may worsen with prolonged work; provide rest periods and eye exercises	Brain can assist or completely distort normal and/or corrected vision
Contrast	Use distinct contrast for different objects if they are intended to be differentiated	Avoid object selections based on similarity between colours or intensities as these are affected by surroundings	
Discrimination	Use constant shapes rather than changing shapes and colours. Avoid lines that are not vertical or horizontal.	Avoid similar shapes that the VRE requires to be distinct – start points and end points or targets.	

2.6.3 Hearing

Audible responses can be usefully employed within a VRE design to prompt, reward or warn users of various issues (errors, boundaries reached, impending changes, etc.) or developments (scores, proximity detection, end of levels, etc.) within the game. Such audio feedback is commonplace and becomes extremely elaborate in fast action gaming. This is often deliberate to guide the user where the game designer wishes them to be, immersed in the environment rather than paying too much attention to actual activity or accuracy of movement. In designing for an ARMaT environment, elaborate audio signals should be limited as the distraction is not required and may be counterproductive. As computer game environments usually contain sounds, absence of audible feedback might be considered unusual to familiar users. Audio feedback can be beneficial and may be an intrinsic part of a therapy or assessment as noted by van Wijck [21] in her proposals for using music to support and engage

people during stroke rehabilitation. However, unless they are being used to assess capability the VRE should use them as simple prompts before, or rewards during or after a session. Clearly, these will need to be appropriate to the potential users. Most users would recognise the value of a simple tone when a target is reached and similarly would enjoy a congratulatory reward at the end of a session.

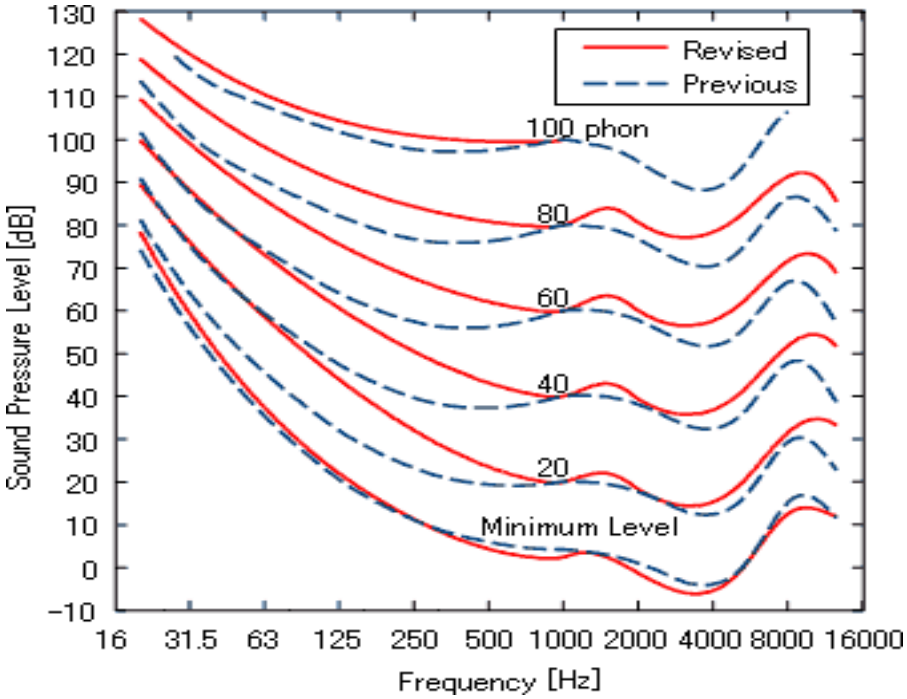


Figure 2-17 Equal Loudness Contours

The human ear has a logarithmic response to external sounds. That is, sounds that may appear to the listener as doubling in intensity or loudness will in fact contain ten times the amount of sound energy. Human audio response is also non-linear across the frequency spectrum as indicated in Figure 2-17 [131]. This requires different frequencies to be adjusted if the designer wishes them to be perceived as being similarly loud.

Hearing also degrades with age, disease and exposure to prolonged or intense noise. Whilst a typical user may possess the nominal ability noted in Figure 2-18 [132], an individual may vary considerably from this. In designing a VRE for measurement that does not require the

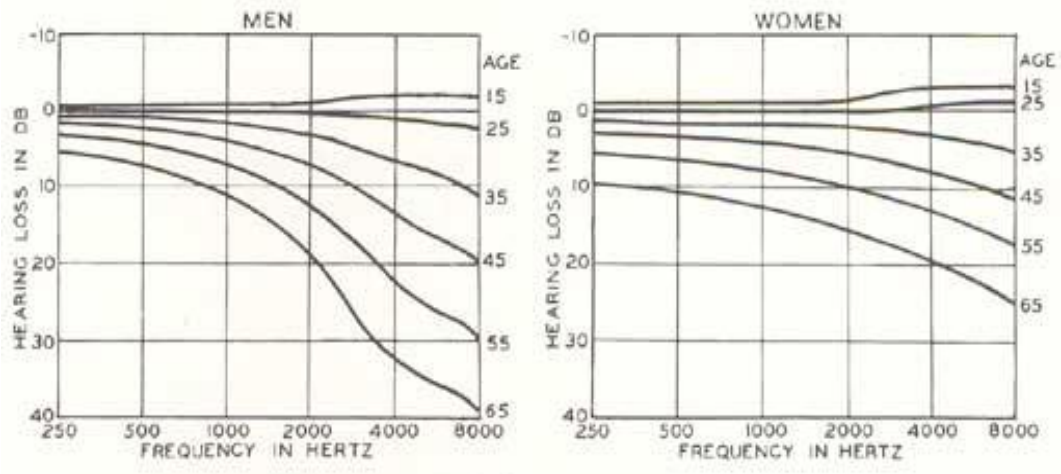


Figure 2-18 Age-related Hearing Loss

user to become completely immersed, audio signals should be limited so that prompts and rewards are understood but not completely distracting to the user.

There has been some research into using audio feedback in haptic applications such as that conducted by Adcock *et al.* [133] which provided auditory feedback to tapping and scratching movements in a VRE. This area and that of tactile interactions has considerable potential for further development.

Summary of Auditory Considerations
The audible components of a VRE are important adjuncts to the visual components but should not be obtrusive or distract a subject from the intended assessment as indicated in Table 2-11.

Table 2-11 Recommendations for Audible Components of a VRE

Auditory	Recommendations	Limitations	Remarks
Volume	Sufficient to make users aware	Users may have limited hearing	Avoid dependence upon auditory cues. Check for recognition of basic cues.
Frequency	Operate auditory content with mid-frequencies such as common musical instruments	Avoid high (above 2000 Hz) and low (below 200 Hz) frequencies	Check for recognition of basic cues
Complexity	Use single tones of simple combinations	Avoid polyphonic sounds unless linked to actual therapy	Potentially add content outside of the main activity as a reward.

2.6.4 Touch

Sensation can be measured in a variety of ways. Typically, light touches felt through the fingers provide a sensation-rich response to the person. Fingertips and other extremities have dense collections of varied surface sensors that allow a tactile exploration of an environment with immediate feedback. The finger tips can have very fine resolution of 0.1 N when compared with typical push buttons tasks requiring 0.5 to 2.5 N [134]. This has been used as a measure of rehabilitation progress [4] as it clearly indicates improved function in discriminating objects and working with the whole hand during grasping actions. In contrast, larger areas of the body such as the palms of the hands contain a lower density of sensors with consequently less fine discrimination of detail and surface texture. However, these sensors can provide a sense of pressure and can detect subtle differences. Additionally, when using some devices such as a handle, the palm sensors interact with the finger sensors to provide a method for feedback control in response to forces or pressures acting on the surface of the skin.

The deeper tissue of the hand contains limited sensors but will respond to larger forces experienced as pressures across the skin and tissue. This should not be required within the VRE although potential applications exist in future for measured weight lifting tasks or response to changes in friction and inertia. The main sensory feedback in normal upper limbs will be the hands and possibly skin surface of the forearm where this may be in contact with a device.

2.7 Haptic Devices

Haptic devices have been investigated as they currently represent the most advanced measuring systems available within clinical rehabilitation. Although the objective of this thesis is to develop a meaningful kinematic measurand, understanding the advantages and limitations of advanced haptic systems is valuable.

Haptic interfaces are a very exciting and rapidly developing area of science and engineering and the subject of considerable research and development for use in medical applications. This rapid development and broad potential applications have resulted in there being few authorities that can be referred to for consistent advice. One reason for this is that haptic devices are not very common and are normally bespoke devices designed for specific tasks such as rehabilitation or medical investigation and training. Williams *et al.* describe one such training application and refer to a number of other haptic applications [135]. Development of devices is progressing rapidly with significant investment in support of recovery after stroke and commercial devices have been deployed around the world [15, 32, 136]. The very nature of these applications requires a wide range of capabilities from fine, tactile actions to gross, load bearing movements. The fact that some devices such as the Phantom© Desktop and Omni® from Sensable® have found many diverse applications indicates a real need and, potentially, a lack of variety in the supply of readily available haptic devices.

The following sections review a variety of projects which were either specifically developed for rehabilitation applications or which might be useful to this research project. In order to focus on the dominant application - assessment and improvement of upper limb sensorimotor function - this research is concentrated on the arm and associated body segments. There is a wealth of additional haptic applications from gait assessment and support to autonomous robotic support for spinal injuries.

The word haptic comes from ancient Greek and means “through touch”. In a broader context, the modern use of the term normally includes any tactile or force-sensing interaction with a device or mechanism. The term can be usefully expanded to include, at least, visual and audio environments often with relevant feedback in these senses. It is common to consider a haptic environment as providing force-feedback in a VRE and most common applications use this. This can be seen in games such as airplane simulations on a PC [9, 93] to medical applications stroke rehabilitation of paretic arm using a robot and simulated work environment [137]. However, haptics can also be used as a guide to provide tactile surfaces or apparent walls across which the user should not pass but which might attract or repel the user [126]. Such activities can provide gentle reminders or guidance to help establish preferred movements again.

Whilst of notable value in understanding the processes needed to support rehabilitation, all of the haptic systems noted earlier have yet to be developed for mass deployment. This may be due to cost, complexity, or acceptance by health care providers. They may also be too large or involved to be suitable for domestic environments. Additionally, some tasks and training environments have been perceived as artificial and of low relevance to patients, being based on a limited repertoire of tasks and training specification although this continues to improve. The majority of the work to date has been influenced by early efforts to assess if this

fascinating technology can be used effectively for rehabilitation rather than assessing what such devices should be measuring and how this can be fed into new rehabilitation strategies.

Whilst this research project did not develop a haptic device, such devices represent the state-of-art for rehabilitation robotics and hence are the most relevant reference area for any new ARMaT devices, as a sub-set of ART devices. In the absence of fully codified design criteria for rehabilitation devices, the most informed solutions for any new device should be based upon the features of such advanced and sophisticated systems. Hence, a review of available haptic devices, paradigms and approaches was undertaken. This investigation provides a valuable reference for the development of the new ARMaT device. Further, it could be used to develop future haptic environments to enhance inter-changeability of data and reliability of the results obtained, something that is notably absent in current haptic developments.

Before accepting that devices that are more sophisticated are always better than simple devices, it is important to note that increased sophistication may lead to a loss of integrity in the data acquired and the subsequent interpretation of results. Where there is insufficient evidence to ignore any anomalous behaviour, the anomalies themselves may hold the key to greater understanding.

In established engineering measuring systems, such as beam bending, small anomalies (caused perhaps by local changes in temperature and vibration) can be discarded as being insignificant to the results. The desired measurement is a large-scale displacement with known material properties and test conditions. With so many unknowns associated with human measurement and interfacing, data sets need to be as true and representative of actual movement as possible. Having developed a believable series of measurements, simplification and filtering of data are potentially possible without loss of important data or underlying patterns.

The addition of haptic capabilities to a known response and measurement would undoubtedly benefit further ARMaT development. However, there are a number of issues that remain unanswered in this relatively new rehabilitation environment. Some of these are unimportant to normal subjects but may be fundamentally important in assessing rehabilitation from a variable and/or unstable clinical condition. Until these are understood, the potential of complex interfaces to distort data must be considered and addressed with great care.

Creating Virtual Realities

Sensorimotor ability, discussed in section 2.3, relies upon a set of prior knowledge that makes sense when combined with learned responses. Whilst this is not always true, it usually means that, for example, bigger objects are expected to be heavier. Other associations are not necessarily appropriate so are not stored in the SCS and CNS during early growth and development. However, unusual associations can still be learned, such as the association of object stiffness and its luminance explored by Jäkel and Ernst [59]. To avoid confusion and the resultant noise in results, VREs need to be representative of real activity if they are to be both accepted and useful. In their experiments with haptic representations Jansson and Larsson [124] identified that unnatural objects were markedly more difficult to identify properly than natural objects such as faces. These were only “objects of simple form” but required significantly more time to identify, and then not always correctly. Jansson and Larsson advise that virtual objects should be simplified and users trained to interpret them. The latter point is largely inappropriate in rehabilitation where developing functionality for

ADL is the main objective. Similarly, any ARMaT device should assess current capability and not be teaching new abstract concepts or shapes.

Whilst any planned VRE for this current research project will be simple in nature, it is worth noting that haptics, whilst fascinating and immersive, may actually pose hidden obstructions to sensorimotor re-learning. They might not only mask progress or distort results due to their inherent complexity, but may also establish inappropriate associations and hence be less than beneficial learning for real world tasks. This is most notable in systems such as Wii® games where, for example, tennis can be played by flicking the wrist rather than making a representative movement involving the whole arm. The fact that there is no representative feedback for a known movement must also call into question the value of such exercises. These issues are discussed in more detail in section 2.8.

2.7.1 Haptic Interfaces

The majority of VREs and associated interfaces rely upon reasonable visual capability to control and operate the systems involved. This was discussed in section 2.6.1 where diminished or unpredictable vision, for example, needs to be accounted for. In addition to minimum physical capacity and capability, cognitive skills need to be established and limitations noted. This is typically addressed in the design of the VRE but to permit full haptic interaction a variety of sensors and actuators are required. Typically, force or displacement is measured and then active drives operate to maintain or modify this force or displacement. Measurement of these data can form the basis of an ARMaT device. Guerraz *et al.* [138] used a haptic environment called *"Texture Touch"* with which they explored the reality of virtual interaction. They identified the following as required measurements in evaluating the validity and /or results of any haptic experimentation:

- Gesture position - displacement along X,Y and Z axes
- Gesture velocity - instantaneous velocity along X,Y and Z axes
- Gesture oscillation - frequency of any movement
- Gesture amplitude - range of movement of a gesture
- Force feedback amplitude - scale of force used to represent the surface texture
- Fore feedback direction – orientation of the haptic feedback

All of these were readily identifiable and very important for their work with the Phantom device used for haptic rendering of objects and textures. They may not be common to all devices nor required for all therapies but they do serve as useful guides or reminders for making an interface believable and hence immersive. It may well be counter-productive to effective rehabilitation if an otherwise believable VRE failed to allow a full range of motion or did not present walls as rigid boundaries in a game or exercise.

2.7.2 Force Transducers

Perhaps the most sophisticated measurements obtained from haptic devices are the interaction forces between the patient and the device, although in some applications freedom of movement or positional repeatability may be the required objective. In all circumstances force measurement is required to maintain control and appropriate levels of safety when interacting with the user [70]. Considerable forces may be imposed by the drives and linkages and these

must only be allowed to act within safe and appropriate limits. This is an important issue, which does not constrain the proposed ARMaT device, as it is essentially a passive device with limited potential for harming the user or therapist.

Whilst the proposed device is not capable of exerting forces directly, force measurement between the patient and device is still possible. This might be achieved indirectly as the device will have inertia and will be subject to friction, and hence forces can be derived from acceleration data. Some of these effects could be modified in order to provide a quasi-haptic environment for the patient although this would really be considered as an additional force-based challenge.

Forces are typically measured directly (using transducers of varying designs and complexities, and hence costs) or indirectly (using simple and readily available components used in an innovative way). The more accurate and precise the measurements, the more expensive the device and hence the system as noted in chapter 3. It should also be recognised that increasing sophistication can lead to unplanned interactions between sensors and actuators and this may, potentially, lead to a less reliable system overall. The following technologies have been employed previously in haptic devices:

Spring balanced resistors - By setting the spring tension to an appropriate value, displacement and hence force can be measured using cost-effective linear or axial potentiometers. A significant limitation of this design is the resulting low stiffness of the interface that the patient experiences which is unlikely to be able to mimic real world conditions in the VRE without complex gearing. Interfacing with a control system is relatively straightforward as line level voltages can be produced and resolution is determined by the range and quality of the resistor.

Commercial Load Cells – Strain gauge or capacitive elements provide high stiffness, accurate and highly reliable and predictable signals for measurement and control. The output signal is readily addressed by computer control systems and this greatly simplifies their application. Inevitably, the cost of such units is relatively high but, in the load range under investigation, these are not prohibitive.

Custom Strain Gauges – With careful design, these devices can match the accuracy and quality of commercial load cells but at a fraction of the cost. The added problem of conditioning and transmitting the resulting signal increases the cost and complexity of any unit that can interface with a control system. However, developments of on-chip amplifiers and conditioners mean that the resulting cost is much smaller than commercial units of comparable specification.

Novel Materials – Quantum tunnelling composites can be supplied in “pills” which may be used to measure forces in dynamic systems (they exhibit creep at constant loads) and can yield predictable results at very low cost. The material is very robust but some ingenuity is needed to develop a suitable mechanical interface to provide a reliable signal from the pill. Signal conditioning is simple but the non-linear response of the material requires software manipulation to yield usable control signals. The material is very stiff and, subject to the mechanical interface, there are no practical limits on the VRE.

2.7.3 Complementary Senses

Whilst not part of mainstream haptic research at present, interest is already being shown in stimulating or utilising the other senses. These can enhance the VRE, making it more immersive or they can stimulate available senses if the primary sense of vision and forces are diminished or absent. As no significant forces are involved, these might be added to an ARMaT device for added immersive qualities or additional challenges as rehabilitation progresses.

Thermal Transducers - The ability to simulate changes in temperature may prove to be a useful area of haptic application. The VRE can be enhanced by simulating cold and heat in the user's hand or other sensing area. This can be achieved by a number of mechanical or thermo-fluid applications such as small heat exchanger using gas or water heat pumps. Unfortunately, their supporting equipment (pumps, refrigerators, fans, etc.), are noisy and add considerable expense. However, Peltier-effect units can achieve modest heat or cold transfer in a small area and require only a controlled current source.

Benali-Khoudja [139] proposes a model for thermal feedback using Peltier-effect transducers and considers the heat exchange of the user's finger on any explored surface. The potential of their model is to assist in the suitable design of a temperature feedback element as part of a VRE. This might be appropriate for users with limited visual acuity or as an enhancement to a therapeutic gaming environment.

Tactile Feedback - The use of tactile feedback to improve selection criteria with able-bodied users was studied by Tahkappaa *et al.* [140]. Use in non-haptic environments has been investigated by Byl *et al.* [46] who identified that improvements in ability were noted following exercise. Whilst Tahkappaa *et al.* found that improvements in speed and error were not particularly significant they noted that the majority of their users agreed that tactile feedback was useful, beneficial, helpful, pleasant or a combination of these. Most users agreed that tactile responses to indicate that the mouse is on target were beneficial.

Simulating surface texture or relative roughness in a VR environment can be achieved in two distinct ways:

Motion Path Modification - by adding small displacement components to any prescribed larger scale therapeutic movement, the impression of texture can be gained. The primary movement generators such as motors can achieve this if movement resolution and control systems are adequate. However, the often conflicting motion paths may introduce unwanted instabilities [55] that may detract from the desired therapy .

Superimposed Motion – instead of using the primary movement generators, an additional, small-scale movement might be introduced by a mechanically de-coupled source such as a small servo-motor. The impression of texture can be implemented irrespective of the movement path and de-coupling the primary drives can help to limit instabilities. Clearly, the vibrations might affect the user who in turn may affect the force transducers but this is a smaller effect and could be isolated both mechanically and electronically.

Magnetorheological Fluids - The use of novel materials such as magnetorheological fluids has been investigated by Bicchi *et al.* [141] in an attempt to simulate medical haptic environments for surgical training. The fluid, which is currently in limited applications in the automotive sector and as potential ballistic armour in military applications, responds to

applied magnetic fields by changing its yield stress. In their experiments, a 180 mm x 180 mm box of fluid was assessed by 50 volunteers who reported close approximation of visco-elastic properties of varied body tissues. When asked to identify an area of increased stiffness 100% of the volunteers successfully identified the correct location. In crude shape recognition tests, 75 - 96% of the volunteers correctly identified the intended shape. Whilst Bicchi's arrangement provided an intentionally coarse measure of position/shape, it may provide additional haptic support for non-haptic ARMaTs and their VREs.

Audio Feedback - Most VREs include some audio content whether it is to signal the start or end of a session, indicate a successful movement or to provide background support to an immersive VRE. Novel use of audio feedback might include setting movements to a beat as used by van Wijck [21] in engaging users to maintain self-practice of beneficial reaching tasks. Audio feedback can also be used to signal position where vision is limited or restricted and this has been used in commercial parking sensors where an increase in frequency of "pips" indicates proximity to an object. This can be applied to VREs to support or challenge users with different frequency or tone feedback signals indicating proximity to walls or targets as is common in vehicle parking sensors.

2.7.4 Control and Actuation

In order to control or maintain motion a driving force is required to react against the forces exerted by gravity and the user. The selection of a primary drive or actuator is not a simple issue of matching primary performance characteristics such as load or speed. The control systems used are often specific to the drives and the cost, space and weight considerations of ancillary equipment can be considerable. The noise produced by some drives may interfere with a therapy session and such distractions are not desirable. For contained, slow speed operations, such as two-dimensional motion on a desktop, the controllability of the drive may be an overwhelming consideration. Even the most sophisticated controllers cannot make a drive perform beyond its inherent capabilities.

Whilst pneumatic and hydraulic actuators are valid solutions to controlled motion, electric motors offer a broad performance envelope within compact, moderately priced standard units. Table 2-12 shows a summary of drives identified in the literature. Additional gearing is often required and this combined with electronic controllers is a common choice for ART devices. Drives and actuators are constantly developing and innovations that provide the required motion should be reviewed periodically to challenge accepted practice.

Table 2-12 Categories of Drives Used in Existing ART Devices

Drive Type	References	Remarks
Pneumatic	[93, 142]	Requires air compressor and associated pipework
DC motor brushed	[23, 89, 143-147]	Low cost and available in a wide range of speeds and torques; readily controlled
DC motor brushless	[96, 148]	Can provide quiet operation over a range of speeds; readily controlled
Solenoids	[141]	Limited movement, typically linear; limited control

Whilst the drives and sensors are the most important components for the mechanical performance of an ART system, the VRE is the part that all users and observers will identify with. Although they have yet to be established, standardised or notably valuable VREs might be transferable between systems to provide consistent and quantifiable results. A large number of VREs have been proposed and used in ART systems and some of these are noted in Table 2-13.

Table 2-13 Categories of Virtual Reality

VRE	References	Advantages	Disadvantages
Games	[51, 86, 93, 149]	Popular and engaging	May trivialise therapy
Driving	[25]	Familiarity of task for adults	Feedback may not be representative of real tasks
Home environment	[150, 151]	Familiarity of environment	
Object/person Recognition	[91, 124, 138]	Specific and personal applications possible	
Control tasks	[29, 48, 68, 77, 87, 89, 93, 126, 140, 142, 148]	Readily monitored and specific skills can be isolated	Might prove tedious for users and not always seen as relevant
Physiotherapy and Functional Therapy	[23, 93, 142, 151]	Beneficial as therapy and assessment	Feedback may not be representative of real tasks

Having developed a useful VRE and a working drive system that responds to appropriate sensors, any ART system must respond safely and realistically to the desired movement. This may be assisting movement for a user with limited capacity or providing a challenging dynamic environment for users with greater function. As with all other elements of this project, understanding engineering processes can assist in understanding biological processes and the most suitable interaction of the two. This was introduced in chapter 1 and developed in chapter 2 where human SCS performance have been successfully modelled [39] on established and developing engineering control theory. This is potentially of great importance as any ARMaT designs must respond to or measure human responses sympathetically. That is, understanding the human SCS may permit more accurate and relevant measurement and control, rather than imposing standard mechanical and electrical measurement and control systems.

There are two basic paradigms adopted in the design and control of small scale robotic and most ART devices, Impedance Control and Admittance Control. They are essentially opposite approaches to achieve the same objective. That is, to permit the user to interact with the device in as free and natural way as possible whilst simulating suitable VRE conditions such as gravity, viscosity, texture, etc. There are a number of modifications to the basic paradigms and hybrid systems which have been proposed to accommodate complex environmental conditions where a simple paradigm has proved inadequate.

Whilst the proposed prototype will not be a haptic system, understanding of these control paradigms and the results of research which does employ them supports other decisions such

as system architecture and VRE content and well as in determining any pseudo-haptic challenges that can be added to the basic non-haptic prototype.

Impedance Control - This control paradigm is best suited to low friction, low inertia systems and has been adopted by many of the smaller haptic devices such as the Sensable Phantom©. Essentially, it registers a movement input initiated by the user and responds with a force that limits movement to represent the required environment. It can be summarised as:

Movement In = Force Out

The need for low inherent friction and inertia imposes limits on the scale and load bearing capacity of devices. A typical continuous load capability of 20 N would be considered large [144]. Whilst this is adequate for many therapies, it is a significant limitation for the wide range of potential therapeutic exercises that might need to bear the weight of a whole body segment. Similarly, the stiffness of these lightweight devices is limited and this is a major consideration for VREs where users are encouraged to explore hard surfaces that may not "feel" realistically hard. However, the inherent lightness of design allows virtually unrestricted free movement that offers good "free-space" simulation. Similarly, they are inherently safer than heavier systems which could exert potentially damaging forces.

Admittance Control - Primarily developed for industrial robots this paradigm registers a force input and then controls movement to maintain the desired force or other simulated VRE condition. Admittance devices require active control to maintain a good "free-space" response as the inherent weight and friction needs to be actively cancelled by control responses. The paradigm can be summarised as:

Force In = Movement Out

In contrast to Impedance Control, the inherent dynamic and physical characteristics of a device designed for Admittance Control are not as limited. Hence, devices can be larger and carry greater loads. The Haptic Master™ is such a device that has a continuous load capacity of 100 N and this has been used extensively in haptic rehabilitation studies. Notwithstanding the improved load capacity and stiffness, certain limitations still exist and speed of response is uppermost amongst these. Clearly, industrial robots can offer very large load capabilities but their added size, weight and cost make them potentially unsuitable for mass deployment.

2.7.5 Human Interactions with Virtual Objects

How people react and interact with a VRE is only part of the issue in designing convincing environments. If the VRE is not realistic to the critical, trained, and refined senses of a human user, then immersion in the VRE will not be convincing. Work by Gillespie and Cutkosky [56] on rendering virtual walls identified the need for, and usual failure in, achieving realistic haptic sensation when "touching" a wall. They describe the instability or chatter (in the order of 10-50 Hz) that people experience due to *"energy leaks"* and attempted to solve this with new control algorithms. Their work centred on the inability of most integrated control systems to sample the required data and act upon it within the simultaneous requirements of a control system and the dynamic VRE.

The rate of data sampling required to maintain stability in the control system is often too low to provide a reliable update in the control system. This is particularly evident in fast moving dynamics, and interactions with stiff virtual walls present such conditions. In a continuous

data stream, such as an analogue clock mechanism or the human body, there are no discrete conditions of kinematics or dynamics; everything can be described as having a continuum of conditions, however complex. In contrast, a digital system is, by definition, divided into discrete quantised values described or existing at discrete time intervals. Digital music is heard as continuous unbroken sound because our ears cannot detect the discrete nature of the signals and they aggregate the steps that are readily measured but not heard. The human ear will rarely be able to detect frequencies above 20 kHz. Hence, sampling and delivering data at twice this frequency is sufficient to capture and reproduce sounds that are essentially indistinguishable from the original music. Similarly, television and film images are perceived as continuous moving images despite their delivery speed of 50 frames per second or less. Our eyes simply cannot perceive or resolve the 50 different images that they receive every second. Digital control systems may operate from a few hundred Hertz in slow moving applications such as belt conveyors to many millions of Hertz in complex safety critical environments.

In designing virtual walls, the contact time involved in impacting against a wall, real or virtual, should be similar in order to convince the user. As this time interval is short, the sampling frequency in the control algorithms needs to be large in order that data is not lost. Haptic control systems such as that used on the Phantom™ operate around 1 kHz and inevitably some data and hence realism is lost between sampled data. There are therefore, two basic solutions: operate the controls at higher frequencies or solve the special case of virtual wall interactions. The former requires high-speed data sampling and control that may be beyond most basic controllers. The second is possible, as demonstrated by Gillespie and Cutkosky, but the overall effects on a subject working within a complex haptic environment is not known.

In their work to solve the problems of human or system induced chatter, Gillespie and Cutkosky modelled the human finger as a second-order linear, time-invariant control element. Their justification for this was based on maximum sampling of 30 ms, which precludes volitional movement. In order to reflect the individual users, they take data from the on-going motion just prior to contact and rendering of the virtual wall. This approach is potentially valuable in addressing data sampling speeds for a new ARMaT device as predictable motion may simplify data appropriate capture processes, these being less sophisticated than haptic wall simulations.

In his design specification for the Phantom™ Massie [146] identifies a minimum stiffness of 20 N/cm (2000 N/m) for users to identify a VRE wall as a solid immovable wall although Brown [54] indicates that 10000 N/m is an appropriate limit. Massie also suggests (p2) that *"meaningful haptic interactions involve little or no torque".* The indication is that, with few exceptions, the user does not need to rotate the wrist, forearm or upper arm about their longitudinal axis in order to carry out appropriate movements. Massie further suggests that *"virtual constraints must not be easily saturated"* and this would indicate that the maximum force that can be exerted by the human finger is approximately 40 N. In fine control this was observed to be closer to 10 N, with average forces around 1 N.

The use of a mechanical interface to permit interaction with a VRE is not a natural activity for many older people. However, older people can master these skills with some training and practice. Children and younger adults who have grown up using computers for work or play

are very familiar with the small scale movements required by a mouse or joystick. Many of the perceptual issues with imagining a 3-D world on a 2-D screen have been overcome by most people familiar with computers. However, some issues still exist. Massie [146] identifies the *"phantom effect"* where users cannot see the rear surface of a sphere as their hand moves through it but their fingertip representation continues to feel it. Similarly, the sensation of feeling invisible surfaces as solid objects can be very convincing. Having become familiar with the "reality" of this environment, falling off or through a surface can be a disturbing but potentially amusing experience.

Wall and Harwin [152] suggest that the most common haptic force feedback systems are limiting because of their single point of contact with the VR environment. They proposed a system using three Phantom™ robots to provide a more realistic feel to the VR interaction. They promoted the use of grounded devices such as their proposed Phantom™ configuration over ungrounded devices such as haptic gloves. Whilst limited to the interaction with fingers and associated movements with the Phantom®, the concept of complex multi-surface or multi-point contacts is an interesting extension of basic VRE interactions.

Research into the use and effectiveness of haptic ART is dominated by the needs and responses of stroke patients. As the majority of stroke patients are older (see chapter 3), the requirements and attendant concerns associated with devices are dominated by those for older people. A particularly relevant therapy for adults is related to driving which requires both manual dexterity and cognitive skills. It is both motivational and challenging for a patient, particularly as this is often seen as a basic element of independent living, which may well have been lost following stroke [25]. Is this a relevant VRE for children? Whilst a child can play at driving, this is just one of many games that they may be interested in rather than being an essential skill and common objective that most adults would desire. Similarly, adults can usually be reasoned with and their experience of working at a problem can be used to promote a therapy and to persevere with it in their own interest. Children do possess these characteristics but their attention span may not be sufficient even when healthy. When recovering from TBI or when being supported with CP, their normal responses and attentiveness may be notably diminished. They need to be provided with additional encouragement and incentives in order that therapies are maintained and the benefits seen to be effective for them.

2.8 Commercial Interfaces

Devices in the gaming industry are notable for their rapid graphics, smoothed motion and rich audio-visual environment. The pseudo-reality of interactive games such as those based on the Nintendo Wii platform has attracted many able-bodied users and those with limited impairments who can enjoy the gameplay at many levels. More recently, specific exercises have been suggested for using such devices as a form of therapy and commercial companies have proposed using existing low-cost games devices to provide a form of rehabilitation. Such gaming devices often contain high-grade sensors that might be able to capture motion. The Nintendo Wii® mote contains a linear tri-axis accelerometer and an infrared camera whilst the Sony Sixaxis contains similar accelerometers and a gyroscope. In principle, these devices can provide reliable accelerometer data via established gaming data streams. The potential for these devices has encouraged a number of proposed interfaces and therapies as discussed in section 2.6.

It is not evident that any of these devices have undergone any structured trials and this may be a reason for the limited deployment of suitable therapeutic games. Indeed, the literature is notably sparse when searching for quantifiable trials. In their paper, Purkayastha *et al.* [153] review the literature is some detail and conclude that there is little objective data to support any suitability of use in trials for rehabilitation. They note (p353) that whilst the devices are potentially very valuable and accurate measuring devices they are typically used for gesture recognition hence *"eliminating dependence on raw motion data".* They cite a number of projects that appear to avoid quantitative data and note that specifications for the devices are often incomplete.

To assess the potential value of these devices Purkayastha *et al.* assessed two common units under strict motion conditions. They found that the two devices behaved quite differently and were better suited to different motions in the ranges (sinusoidal motion at 1 Hz and 4 Hz with amplitudes of 7 mm and 49 mm) that they examined. They concluded that the devices were reasonably faithful for motion shape and would probably perform better over larger distances, but this was not quantified. The most notable element of Purkayastha's work is the use of a periodic motion signal. As discussed in section 3.2, the filters and approximations used in numerical methods can be adjusted to fit periodic data and obtain a reasonably faithful measurement. However, discrete point-to-point motions are not readily extracted from such digitally derived data. This was also illustrated in the graphs produced by Purkayastha et al. The accelerometer data usually indicated a variable phase shift (probably due to communication delays) and sporadic attenuation of acceleration values. However, more importantly, the endpoints of the test were significantly distorted and not representative of the true periodic motion. It is therefore reasonable to conclude that non-periodic motion and perturbations to otherwise periodic motion would not be faithfully reproduced. Hence, such devices are unlikely to be suitable for quantitative assessment of even simple reaching tasks.

The limitations of using advanced low-cost PC interface devices such as the Wii Kinect™ system were noted in chapter 3 and have been highlighted in this project as having potentially serious limitations. Even when a basic PC mouse was used in an operating system designed for graphics a number of issues arose. It was evident that the algorithms used to translate mouse motion to screen cursor motion were distorting real pathways and/or times of motion to meet a required trajectory. The software permitted various trajectories to be interpreted

rather than recording actual movements faithfully. Hence, ballistic components of mouse movements (typically from a fixed starting point) were simplified into a few data points providing an approximate path until finer movements were flagged. Indeed mouse positions on the screen are often blurred and/or transitory relying on the user to correct movements in real-time. This is generally due to the computational over-head of reading the mouse data, interpreting it and interfacing this accurately to the visual environment of a program in real-time. The mouse movement in most programs and games is a means to an end – selecting a menu or similar in another program – rather than being the main object of interest.

How the mouse-cursor gets from a start point to its desired endpoint is approximated by the software based upon rapid movements within a scaled world. Typically, mouse movements are very much smaller than their screen representations and the algorithms in the software provide a quick and inaccurate solution that meets a need. Fine motion at slow speed can be a faithful representation of the true motion, even if scaled. However, this does not occur at higher speeds and over longer distances, such as the true width of the screen. Special gaming mice are available with enhanced resolution and an apparent ability to deactivate the smoothing or approximating algorithms used in a "normal" mouse. However, it is not known how any commercial gaming software interprets this raw data.

When combining a biological understanding of rehabilitation and learning/re-learning processes with an engineering appraisal of VREs and commercial gaming interfaces some subtle limitations became evident. The author has played a number of Wii® games and, whilst engaging, they do not reflect real movements and real reactions. There is virtually no force involved in the action of "hitting" a ball, beyond the arm's movement and minimal weight of the device. Although accuracy of motion has not been tested it is notable that most of the gaming industry devices, whilst capable of reasonable resolution and accuracy, do not appear to be using this true capacity within the game. In addition, it is possible to "cheat" the system. Children can easily demonstrate that a game that should require full arm motion, such as tennis, can be reduced to a flick of the wrist. This is not a particularly valuable exercise but a user achieving a high score in this manner may believe in their progress when none was actually made.

Inappropriate exercises are perhaps a waste of time and effort for a patient requiring real rehabilitation but this may be the least significant concern. Potential problems exist and may become evident in time as these devices become more popular and accessible. The unnatural reduced motion required to "cheat the system" may potentially damage muscle and tendons with repetitive strain injuries due to near zero forces over very small distances. This is an artificial "minimal work-done" issue whereas real motions require work to be done. Perhaps even more damaging is the potential waste of available neuro-rehabilitation processes. By forming new neural pathways utilising the brain's potentially limited plasticity, new learning and sensorimotor function can be achieved. However, such games may waste this valuable resource on valueless motion.

The motions described by devices such as Wii™ can be highly complex and apparently realistic to a casual observer. However, within the rehabilitation environment, it is of potential concern that the motion of the user may not be accurately captured and forces involved are either not present or not representative of the intended task. In summary, the following are

areas of concern in using commercial interface devices for true recording of motion that may advance our understanding of the neuro-rehabilitation process:

- Required movements may not be realistic or valuable
- Game responses may not faithfully reproduce all movements made
- User reactions are not representative of real activity
- Data capture is deliberately modified to improve the game not the exercise
- Visual rendering may be scaled asymmetrically
- Time or phase lags distort the valuable visual and proprioceptive feedback
- Games are typically designed for users rather than addressing a measureable rehabilitation need
- Success or failure in a game may not reflect true ability
- Valuable and limited SCS and CNS rehabilitation potential may be lost

It is highly questionable whether such environments are suitable for measuring progress or response to therapy as many motions and apparent achievements can be reached through non-representative movements. Even if the motion capture were faithful, the results shown to the user or therapist are centred on achieving a Level of game play. There is no evidence that achieving sufficient points in level 1 is representative of any real achievement. Hence, changing the task or difficulty in level 2 may be beneficial or it may not. There is certainly no evidence that passing all levels shows a quantifiable and appropriately progressive improvement in any useful skill or sensorimotor capability.

Ideally, commercial games systems could be adapted to provide faithful, real-time data recording of true movements that were constrained to be real and valuable. If passing each level was quantifiable and benefits to a patient were documented at each stage or implied by statistically relevant analysis then such systems would be of great value. Perhaps this can be achieved using the rapidly advancing technology from the games industry. It will however, require considerably more scientific justification than exists today.

2.9 Chapter Summary

This literature review has covered a wide variety of subjects and sources to prepare for the design and testing of a new ARMaT device. The principal areas cover the very different worlds of biological and engineering applications and the interdisciplinary merging of these extensive fields to support health care and quality of life. Prediction, assessment and rehabilitation of common conditions are undergoing continuous development and support for the design and implementation of new products is evident in the adoption of some significant commercial applications.

The literature review has provided guidelines for establishing a new and credible assessment based upon kinematic measures of simple reaching tasks. It has indicated that many existing assessments, whilst extremely valuable for users and health care providers, are qualitative and are not reproducible outside of prescribed limits. Despite there being a multitude of possible assessments, few are used routinely as they often involve significant time, effort and/or resources.

It is clear that there is a significant need for a quantifiable measurement system that can be used reliably and quickly. Equally, such a system needs to be designed and implemented with care to avoid masking the data that it is seeking to uncover. Many of the systems described in the literature do not refer to the effect of the VRE on the user, or how it was designed to maximise accuracy or integrity of responses. The literature was reviewed for guidelines in designing VREs to address this concern by identifying perception issues for the primary senses of sight, hearing and touch. These guidelines will be used to develop an interface that minimises unwanted effects from the VRE and these are discussed in chapter 4.

Although it is not intended to develop a haptic interface for this current work, the work of others in developing and testing sophisticated ART systems offers valuable reference for designing an ARMaT device. There is growing support for their use and the data that they provide and, as more devices become familiar in hospitals and clinics, such data will become more reliable. Hence, this fascinating field has been reviewed for valuable guidance, which will be incorporated in the design development documented in chapter 4.

Gaming systems and sensors were examined as the most advanced, cost-effective sensors available to open market applications. Their use is questioned where the raw data cannot be extracted and where quantifiable progress cannot be determined. Virtual environments are considered the most effective in supporting rehabilitation where they are based on simple visual and audio content. This minimises the potential for corruption of natural movements by overly complex interactions and user interpretation of an unnecessarily complex environment.

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3 Methodology

This chapter presents the methodology used to investigate, design, develop, test and validate a new ARMaT device. The nature of this research project requires a robust methodology to permit a suitable specification to be developed, that relevant technologies and processes are employed, and that reliable data is gathered and analysed in a transparent manner. The process employed was intended to facilitate the structured and traceable development of a prototype suitable for clinical testing. The methodology was also intended to facilitate further developments of this device towards commercial application. In developing the new ARMaT device a phased approach was employed, based upon new product development considerations taken from the author's experience in design and manufacturing industries.

ART and related technologies continue to develop with more extensive and elaborate testing providing greater insights into their immediate and long-term potential. In seeking to address a multitude of conditions and states within a condition, it is unlikely that a universal solution can be found. This explains the historical development of unique assessment and treatment systems which address specific patient issues. However, the growing multi-disciplinary collaborative approach between engineers, clinicians and therapists has yielded some notable successes. The InMotion ARM™ and related technologies described in section 2.5 present the benefits of continued development from research to commercialisation to good effect. The device offers assessment and rehabilitation of the upper limb based upon considerable development and testing with stroke patients and this has been extended to applications with CP and TBI [154].

The extensive work with stroke patients outlined in section 2.5 offers guidance on the performance criteria, operation and control, data required, and anticipated measurands that might be used in a new ARMaT device for the chosen CP participants in this thesis. These design aspects have been investigated to provide a starting point for the specification of the new ARMaT device.

This chapter describes the following phases that permit subsequent design development, testing and analysis:

- Identification of Potential Users and Costs
- Investigation of Performance Criteria
- Identification of Potential Parameters
- Data Capture and Processing
- Statistical Assessment of Potential Parameters
- Planned Development

3.1 Potential Utilisation

One of the guiding aims of this project was to make appropriate devices available to those who require them at a cost and level of complexity that will not be a barrier to use. Whilst there is a significant potential for supporting the known conditions and associated rehabilitation efforts noted in section 2.2, the cost of most existing devices makes them prohibitive to the majority of potential users. Similarly, the size and complexity of existing devices might preclude use in the home or local clinic even if their cost were reduced by mass-manufacturing techniques and economies of scale. Therefore, a review of potential users, affordability criteria and applications was undertaken to establish the potential for introducing a new device.

Affordable ARMaT devices with a proven capability would provide an opportunity for many users to gain access to cost-effective, relevant and beneficial assessment and might potentially release some therapist time. There are a number of possible applications for such devices in three major treatment environments:

Hospitals:

- In-patient PT/OT - supporting therapist to assess repetitive tasks
- Early intervention - rapid low-impact basic assessment and exercise
- Close monitoring - repeated assessment with minimal therapist commitment
- Diagnostic assessments - reproducible quantitative data on progress/response
- Preparing for out-patient clinics - self-directed practise under supervision
- Advanced staff training - use of enhanced features and assessment of measurands
- Feedback to clinical studies - data capture on response/progress to planned interventions

Clinics:

- Out-patient PT/OT - self-directed activity under supervision
- Continued treatment - progressive challenges and assessments
- Supervision/encouragement – measurement of actual exercises completed
- Updates for home user - develop and introduce new challenges in clinical setting
- Staff training - use of basic features and understanding basic measurands
- Feedback to clinical studies - mass data capture on response to sustained clinical regimes

Homes:

- Self-assessment - patients can challenge themselves and receive feedback
- Long-term assessment - independence from central resources
- Remote supervision - therapist/clinician can access data from home exercises
- More complex exercises - challenges responding to increased ability
- Fine motor control - assessments for wide range of motion
- Feedback to clinical studies - mass data capture on response to sustained domestic use

Each application may demand different requirements from the device, such as durability and enhanced safety in clinical environments, or greatly reduced cost and potential compromised performance in domestic applications. However, the key measurands will form the basis for all devices.

The principal user groups and applications were introduced in section 1.3 to set the context for this thesis. This section investigates the range of medical conditions that currently employ significant PT/OT/ST resources within clinical and domestic settings in response to the demands of patients. By understanding the conditions, and the therapies employed to treat them, a better understanding of the potential for a new measurand can be developed as well as potential measurement parameters. Many conditions share similar issues in rehabilitation as noted in section 2.2, as they often share similar aetiology and rehabilitation outcomes. Hence, measuring each with a similar "ruler" should provide cross-disciplinary advantages in clinical assessment of existing and future therapies for a wide range of conditions, treatments and therapies.

The potential application or user base for such a metric has been identified from the known populations in each patient group associated with a particular condition. This is significant in the UK alone, and the opportunities worldwide for such rehabilitation measurements to inform subjects and treatments are considerable. As such, there is a substantial "business case" for such developments.

The consequences to patients and families of ABI represent a growing challenge to health care providers across the age spectrum. As the population ages, and as survival rates increase with improvements in medical care, demands on limited resources will increase.

ABI includes conditions such as CP, CVA or stroke and PD where various mechanisms result in partial brain death or failure of coordination due to chemical deficiencies. It also includes TBI resulting from physical injury or surgery. This mechanism, symptoms and treatments were discussed in chapter 2.

Current challenges in conventional therapy are dominated by significant demand on limited resources. Limited provision, and hence treatment, may preclude realisation of a patient's full potential for recovery. Similarly, quantitative data for established and new rehabilitative practices is not generally available to inform when to continue or change therapy. Hence, patients may not be receiving optimal treatment as the expense cannot always be justified or equipment is simply not available. The quantitative (frequency, duration) and qualitative (nature of practice tasks and performance feedback) aspects of optimal rehabilitative strategies are still not well understood [46, 60, 155]. Both issues are potentially addressed by a quantitative measure of performance that can reliably measure progress along a continuum of ability. This continuum extends beyond established ranges for specific conditions or stages of a condition, as noted in section 1.5.2.

Using a virtual physical environment in which patients can perform challenging and interesting exercises is considered to be a progressive step in providing rehabilitation. The use of game-playing or other motivating virtual environments whilst experiencing simulated gravity, friction, texture, etc, have been explored and observed to be beneficial to most patients [21, 48]. Similarly, devices that facilitate or obstruct attempts to complete specified movements provide further challenges that promote recovery of function [86, 156].

Previous work in this area has emphasised the potential health-economic benefits of large scale "automation" of therapy [89, 136, 157]. This requires not only technical advances to lower construction and operational costs of devices, but major advances in understanding of optimal rehabilitation regimes. In progressing toward these however, more immediate and previously underemphasised benefits may develop in a truly multidisciplinary interaction between therapists and engineers. These may include the identification by therapists of potential new strategies and their systematic comparative evaluation by using objective biomechanical evidence.

3.1.1 Principal Patient Groups

Given the wide ranging applications that any ARMaT device could be designed to investigate and accommodate, the patient groups that may benefit from a new metric are equally large and diverse. The following sections introduce the scale of existing conditions and identify the potential numbers of patients in each group that could benefit from a broad introduction of accessible rehabilitation measurements. In effect, it represents a basic market survey of potential users, be they private or institutional. Some conditions are dominant in particular age groups and these are identified specifically. Others may affect all age groups and the onset is not predictable but survivability may be more likely in young to middle-aged (16-50 years) adults.

The working population (16 to 65 years) is identified as these people represent the most significant economic group, being the greatest contributors to wealth whilst being the least dependent upon health care. All data is subject to local and national environmental and economic factors, health care provision and local support systems. As such this data can only be used as a general predictor of potential users. In the following tables, incidence is a measure of new cases of the condition each year and prevalence refers to the number or proportion of a population that live with the condition.

Table 3-1 shows the relevant statistics for children aged five to sixteen years for common conditions. This is the main subject group for the current work and the conditions noted are the most relevant to the immediate application of the work contained in this thesis.

Table 3-1 Paediatric Patient Groups

Country	Condition	Incidence	Prevalence	Data source
World	Traumatic Brain Injury	100-300/100k		[158]
UK	Cerebral Palsy	0.25% of population	0.25% of population	[159]
UK	Friedrich's Ataxia		2/100k	[160]

Table 3-2 shows the relevant statistics for adults aged fifty to ninety years for the most common conditions. Table 3-3 shows the relevant statistics for the whole population where a condition (which currently benefits from PT/OT) affects people of all ages without specific age bias.

Table 3-2 Geriatric Patient Groups				
Country	**Condition**	**Incidence**	**Prevalence**	**Data source**
UK	Stroke	160/100k	1,100k	[161]
UK	Parkinson's Disease	1/500	127k	[162]
USA	Stroke	190/100k	8,600k	[163]
USA	Parkinson's Disease	60k	1,000k	[164]

Table 3-3 Conditions without Age Dominance				
Country	**Condition**	**Incidence**	**Prevalence**	**Data source**
UK	Traumatic Brain Injury	150k (minor) 10k (moderate)	120k	[165]
USA	Traumatic Brain Injury	1000k (treated) 230k (survive)	5,300k	[166]

There is evidence that PT/OT/ST benefits people with mental health issues, which may be as diverse as depression to schizophrenia, and work using rehabilitation robotics with autism spectrum disorders (ASD) and other cognitive diseases has been noted [167]. It is possible that a new ARMaT device may support assessment of this patient group. Table 3-4 shows the relevant statistics for the whole population where a condition affects people of all ages without specific age bias.

Table 3-4 Mental Health Related Issues				
Country	**Condition**	**Incidence**	**Prevalence**	**Data source**
UK	Depression, anxiety, etc,		1.4 to 9.7 % of population	[168]
UK	Dementia	163k	820k; 1.4% of population	[169]

Table 3-5 shows the relevant data for people aged sixteen to sixty-five years and is primarily based on data for the working population. Clearly, having retired from work, the condition does not cease to be present but may not be reported in the relevant statistics anymore.

The literature indicates that the vast majority of patients with ABI are prescribed and benefit from some form of PT/OT/ST. Clearly, each individual case will require varied therapy, some of which is unlikely to be readily measured, such as whole body exercises involving posture or gait. However, people with conditions such as ABI, TBI, works injury, PD, arthritis and mental health issues comprise the dominant population of potential beneficiaries from ARMaT.

Table 3-5 Works and Sports Injuries				
Country	**Condition**	**Incidence**	**Prevalence**	**Data source**
UK	Works injury affecting upper limb requiring more than 3 days off work.	37,822 (2003/4);	448,000 (2003/4 upper limb and neck)	[170]
USA	Works injury	1000/100k		[171]
Works injury includes Repetitive Strain Injury/Cumulative Trauma Disorders				

It is recognised that a detailed market assessment would be required to justify investment in any new device. However, the basic review suggested below serves as an indicator of a potential market using what might be considered insignificant portions of a population. Table 3-6 shows the potential beneficiaries of this research based upon the assumption that only 1% of more developed populations and 2% of less developed populations result in long-term loss of arm movement. The difference suggested here is based upon more advanced health care provision being available to populations in developed countries, such as the rapid use of treatments for people experiencing a stroke. Given the potential disparity in access to medical care and treatment the potential beneficiaries of an ARMaT device are assumed based upon 10% of the prevalent population in more developed world and 1% of the less developed world. Again, this ratio is used to indicate that access to treatment, for acute and chronic conditions, could be notably different.

Table 3-6 Summary of Potential Beneficiaries			
Country	**Population (million)**	**Prevalence Populations (million)**	**Potential Beneficiaries (million)**
UK	64	0.64	0.064
Europe	740	7.40	0.74
USA	316	3.16	0.079
Japan	127	1.27	0.127
China	1,357	27.1	0.271
India	1,277	25.5	0.255
World - more developed	1,246	12.5	1.246
World - less developed	5,891	117.8	1.178
World - least developed	0.886	0.02	0.0002
World - total	7,137	130	2.42
Population data source: Population Reference Bureau 2013			

By simple extension to the world population, the potential beneficiaries (and hence a potential economic market for upper limb ARMaT) would be over one million in more developed countries and over two million worldwide. As noted earlier, this is conservative estimate and

is based upon basic assumptions. The purpose is to identify whether development of a new ARMaT device might be useful to a significant number of users.

3.1.2 Target Costs

If a device is to be accessible, it must be affordable and available. Hence, the cost of delivering a device for testing and final deployment has been a cornerstone in decision making processes throughout this project. Large-scale deployment can benefit from economies in mass manufacturing but only if the device can be manufactured from readily available components and materials. If costs are to be minimised then complex components, assembly, testing and maintenance should be avoided, or limited to key elements, where deemed necessary. A simple design is typically a reliable design, so simplicity has been a guiding principle in the use and selection of components and materials. As noted in section 1.1, simple measurements are the key to believable assessments and hence a simple device and application might also be appropriate for the most believable measurements.

The office for national statistics (ONS) publishes data for gross disposable household income (GDHI) [172] which is the money available to households after payment of taxes, etc, but excludes basic living cost. In 2011 the UK average GDHI was £16,034 per year (£308.35 per week), with significant national variation. Similar assessments from the ONS for the European Union member states indicate that this average figure is common across most of Europe although predictable variations exist.

Average (inflation adjusted) weekly spending is identified by the classification of individual consumption by purpose (COICOP) is an internationally agreed measure of expenditure. This has been decreasing since 2001 and in 2011 was averaged at £483.60 [173]. A similar measure, the family expenditure survey (FES) has been used in the UK and continues to be compared with the COICOP data. The FES data shows an average household expenditure of £481.20 for 2011 [173]. The discrepancies between the GDHI, COICOP and FES are due to reporting differences.

Based upon a simple assumption that a household might spend up to 10-15% of the GDHI to support a significant medical need (13% was spent on “leisure and cultural” activities in 2011), it is likely that a new domestic ARMaT system costing more than £2000 may limit mass deployment. Clearly, charitable support and medical funding may reduce the cost and devices might be rented or loaned.

Given a typical commercial mark-up of 100%, the manufacturing and production costs would need to be less than £1000, although clinical variants could justify much higher costs based upon continued use. The design must therefore be based on a very simple platform to achieve such low manufacturing costs. Specialised variants could be developed from this platform to meet demands for improved longevity and, potentially, additional functionality. Replacement components and materials could be sourced that will provide more reliable operation of a standard design under commercial/industrial use. Useful comparisons can be made with the design and supply of affordable domestic blood pressure monitors, pulse-oximeters and wheelchairs compared with those used in hospitals. However, it is unlikely that, for a standard design, even these modifications will make the production costs much greater than £2000.

3.2 Performance Criteria

In order to progress a design for a basic ARMaT platform, performance criteria need to be established to ensure that appropriate measurements can be made. Some latitude in the range of these criteria is necessary to permit development and refinement as the concepts and prototypes evolve. Without this, decisions made earlier in the design may limit further required potential development. For example limiting a data recording frequency to a low value may preclude accessing newer and faster sensors and actuators. However, relevant initial performance limits need to be established so that potentially useful solutions are not discarded because they cannot meet unrealistic criteria. The design and performance capability therefore needs continued review against believable criteria that can be justified at each stage of development. The following sections identify the most significant criteria to be considered when developing the design, which is discussed in chapter 4.

Machines can measure movement relatively easily using readily available sensors that interface reliably with computers and VREs. Given this facility, it is often tempting to measure all movement. However, the number of measurements and their quality can cause problems with data handling unless very sophisticated systems are employed. Table 3-7, discussed later, shows the types of measurements that would be reasonably achievable using low-cost technology. Given that the anticipated movement metrics required are not universally agreed upon, more data is considered to be an advantage. As noted in chapter 1, the proposed prototype is not intended to be a haptic device at this stage but measuring or deriving force can be valuable so it was included.

Accurate and precise measurements are relatively simple for most machines, whatever their geometry, although increased accuracy and precision do attract increased cost and complexity. It is important therefore, to decide on the level of accuracy required for therapy and rehabilitation tasks if minimum cost is to be achieved without compromising functionality. Within established PT/OT exercises, typical manufacturing grades of accuracy and precision are not generally applicable for recording gross movements of the upper limb. The level of detail is not only difficult to achieve when interacting with a human subject, it is also largely irrelevant to existing and potential therapies. A therapist may seek to improve a reaching task so that the patient could support their ADLs by picking up a pen, for example. This qualitative measurement is more use than identifying if the movement were quantifiably more accurate between therapy sessions. However, any new ARMaT device will require quantifiable results and hence greater accuracy and precision than that of any standard PT/OT assessment.

3.2.1 Measurement Quality

Whatever measurement is required, the quality of that measurement must be determined in advance in order that the correct sensor and processing system is selected and then operated within its declared range. All measurement devices and systems contain inherent errors of reading, conversion, operation, transmission or manufacture. They may even degrade with age or use and may need recalibrating. In addition, there are errors introduced by environmental factors and human intervention as well as random errors with no identifiable source or control strategy. By specifying the most appropriate integrity measures for the device and system such errors can be accounted for, or ignored. The following is a simplification of standard metrology terminology so that realistic and reliable sensor and data-processing decisions can

be made. A more detailed description is provided in [174] and the following terms and be reviewed in this reference.

The substantial issues of data conversion and processing and the use of numerical methods and related statistical assessments proved a notable challenge for a simple ARMaT device and these are discussed in detail in section 3.4. It is important to understand that most measurements are analogue in nature and many sensors are typically analogue in operation. They require analogue-to-digital conversion (ADC) devices to produce the digital data that is usually required for commercial data processing and control systems.

The following sections are supported by appendix 3A which identifies typical engineering measurements. Related concepts in biological measurements are noted to identify similarities with engineering measurements and to clarify common misconceptions encountered in the course of this research.

Range
The range of a device is the limit of its reliable and repeatable measurement. In a clinical context, range of movement would be assessed. This has limits due to geometry, kinematics and dynamics of the required movement, the limb/body, and the task involved. Gross movements may have a wide range whilst fine movements a more limited range. Most movements are achieved using the non-linear linkages formed by the limb and torso and are hence generally non-linear. Indeed movement at extreme range or when facing a simple weight or force challenge can be disproportionately difficult to achieve, so any measurement must account for this.

Accuracy
Accuracy defines the closeness of a measurement to a known standard. Selecting the most appropriate level of accuracy over the desired range will determine cost and possibly reliability. It is possible to achieve high accuracy but the movements being measured are unlikely to justify such a selection. Existing rehabilitation exercises or assessments are seldom driven by desire for high accuracy, as this is difficult to achieve and may be meaningless. Sufficient accuracy in support of feeding and dressing may be largely unaffected if limb movement varies by 5 mm. They may be enhanced with better accuracy but an accuracy of less than 1 mm would be unusual. Writing and manipulating small objects does require fine movement control (less than 1 mm) but only skilled crafts will require more accurate placement and control. For a placement assessment such as putting an object in a desired location or moving a mouse on a PC, accuracy can be assumed from successful completion of the task. However, the actual placement of the object or cursor may be several millimetres from the centre point of the target.

Resolution
Resolution is the smallest measureable increment in a range at the required accuracy. In rehabilitation assessments, resolution may be reflected by the ability to place an object or pointer on discrete targets within an array of targets. The ability to distinguish between the points and move towards them is a measure of refined ability. Clearly, there are sensible limits to pointing tasks and identifiable targets should be spaced so that they are achievable at any stage of recovery. In early stages widely spaced targets (10 mm to 50 mm) may be achieved consistently with care whilst latter stages may offer the challenge of targets spaced

just a few millimetres apart. Refined skills such as writing may require a working resolution of less than 0.5 mm.

Precision
Strictly speaking, precision is a measure of repeatability but this term is rarely used in this engineering context, being more normally confused with accuracy or resolution. Precise movement however, is possible and is probably the best analogy to be taken from engineering measurements as repeatability is extremely important. Success, (howsoever determined) may be possible in many but not all movements in a multiple reaching task assessment. If the degree of success were assessed by statistical inference then improved repeatability, that is precision, would be an indicator of improvement. Adjusting the challenge would allow a further measure of precision and an indicator of progress in a task.

Time Measurements
Accurate time measurement is relatively straightforward with modern digital devices. A therapist may use time as an indicator of success as noted in chapter 2. Reducing the time to complete a task is a measure of improvement in much the same way as a sports trainer may measure lap times or overall time. Obviously zero lap time is impossible and norms for different ages, sexes and abilities can be established. As these norms are approached, the effort, skill, or other factors become disproportionate to the possible achievement so it is important to establish variations and norms for a stage of recovery and possible clinical condition, as noted in chapter 1 for the continuum of ability.

A more challenging use of time measurements is to attempt a task within a precise time frame. The task would be achievable in less time but must be completed in a fixed time. The cognitive and physical challenges are quite different to those needed to minimise time to target type assessments, perhaps by sacrificing accuracy and precision. They are particularly valuable as they do not contain any obvious floor and ceiling effects if the movement is carefully considered. Obviously, jumping or throwing is impossible to slow down below a sensible limit, as are many ballistic reaching tasks.

Endurance is often measured by time when maintaining a level of exercise for as long as possible. This is not a typical assessment for early stage rehabilitation and might not be appropriate when considering accurate and precise movements.

For all time-based assessments the raw data is simple, predictable and reliable when based on digital clocks and related data acquisition systems devices.

Positional Measurements
The most obvious measurement for upper limb rehabilitation is position or displacement and these are routinely taken in most ART systems and PT/OT exercises. Moving from position 1 to position 2 to pick up a pen requires a displacement of X and/or Y and/or Z mm. How this measurement is achieved is discussed later but, for basic Cartesian displacement, reliable and suitably accurate measurements in X and Y (2-D) or X, Y and Z (3-D) are required. Polar coordinates (radius and angle) may be more appropriate in rotational devices and conversion between these two reference frames is simple and predictable.

In order to identify small changes in ability, an appropriate level of accuracy, etc, of recording movement is required. Typical accuracies of 1 mm over a range of 500 mm (0.2% resolution) with a precision of 0.5 mm would be considered appropriate to define the large scale and fine

positioning abilities of the upper limb. See chapter 4 for details of previous research in this area, particularly related to sophisticated haptic environments. Greater accuracy is possible but is unlikely to be required.

Velocity Measurements

Simple bulk speeds can calculated from total path distances divided by the time taken. The overall displacement is accurate and the time taken relatively large, hence limiting calculation and ADC errors. Intermediate or discrete velocities along a path can be calculated in a similar way but suffer from numerical errors and often require filtering or smoothing algorithms to produce recognisable outputs. The small time steps typically used to divide the variable displacements can result in unrealistically jerky calculated velocities, which are rarely observed in real movements. Whilst a large time-step (effectively an averaging filter) will minimise this, too large a time step will not capture small and potentially significant detail.

The treatment of raw data to overcome some of these limitations is discussed in detail in section 3.4. However, the general shape of the velocity curve in a typical long reaching task can be used as a benchmark for normal subject ability. It is commonly observed to be bell-shaped, with initial acceleration towards the target, a period of near constant velocity and finally, deceleration to the target as described in section 2.3. The shape of the curve can be dependent upon the length of the reaching task, the perceived urgency of the task and/or specific instructions.

Some clinical conditions are adversely affected by rapid movements as the muscle tone can increase as the velocity of movement increases. This must be assessed before attempting speed challenges or when drawing conclusions from data indicating low bulk velocities, which might have resulted from velocity induced tonality in some or all muscle groups.

Acceleration Measurements

As noted for velocity measurements, some patients may respond unpredictably when accelerations are introduced or required in an assessment. Any limitation must be determined before a therapy or measurement session progresses to avoid confusion or disappointment to the patient. Accelerations are a valuable part of an assessment tool as they indicate the ability to react to a challenge and, for a given mass, they indicate the ability to manage a force challenge which might reflect an ADL, such as opening a door or moving a book on a table.

Force Measurements

Exerting and reacting to forces occur continuously during normal activities and hence these are familiar challenges that can normally be achieved by normal subjects. Where the SCS is impaired, force sensing or reactions to a sudden imposed disturbance may be impaired. Consequential movement and control may become unpredictable and this should be identified before any force challenge is implemented. It is anticipated from the work on haptics that such a challenge will be an advanced assessment tool for future devices.

Absolute and Relative Position Measurement

The dominant measurement considered by the main hypothesis in is position or displacement and this must be considered in some detail. Absolute measurement of position is possible with a number of direct or indirect reading devices. More commonly, relative movement is used as this requires less sophistication, although the system needs to establish a starting point from which to measure. Typically, the starting point is set before any movement is initiated. There

are limits for both approaches. Absolute measurement may cost more to include as sensors are typically more sophisticated and hence expensive. Relative measurement can suffer from interruptions to data sampling or processing which can lead to partial or complete loss of integrity. If a data set is lost or corrupted, the next reading from a relative device will be accurate but its position in space is not known and hence precision is lost. Absolute devices will continue to provide true measurements even if some motion is lost or corrupted. As none of the measurements are used in safety critical applications and tests can be repeated if data is corrupted, lower cost sensors may be acceptable.

The preceding discussion is summarised in Table 3-7 to facilitate decisions on which measurements were useful to include in the proposed ARMaT device. They are not exhaustive but inform the project's development and will be considered in more detail in chapter 4.

Table 3-7 Summary of Potentially Useful Measurements

Measurement	Data recorded or derived	Remarks
Position, displacement (mm)	Basic XY (2-D) or XYZ (3-D)	Commercial sensors offer good accuracy, resolution and precision at moderate cost.
Time (s)	Readily recorded	High accuracy and resolution possible at low cost
Velocity (mm/s)	Velocity sensors are expensive and/or large. Can be derived by differentiation/integration of other sensor data.	Errors and loss of authenticity is probable with all numerical processes.
Acceleration (mm/s^2)	Can be measured directly using low-cost accelerometers.	Potential for noise and cross-coupling effects from low-cost accelerometers.
Force (N)	Can be measured using affordable transducers. Can be derived from acceleration data and known masses, etc	Potential for cross-coupling on multi-axis force measurements. Validity of force measurements from derived data needs to be assessed.
Data handling	Real-time data processing and storage limits will affect the number and time-density of coincident measurements.	Real-time processing is essential for VRE interaction to avoid time lags and potential distortion of feedback signals to users.

3.2.2 Integrity of Measurements

If decisions are to be made on the basis of metrics derived from measurements of movement of the upper limb then the integrity of each measurement must be as high as is reasonably possible, and any errors understood and reduced below the basic accuracy required for assessment. Similarly, errors within sensors, signal processing, ADCs and interpretation of results should not compound to introduce unplanned or larger errors than expected.

The author had considerable concerns over the validity of many velocity and acceleration measurements in the literature reviewed as the raw data is notably modified by unknown or poorly documented algorithms. In discussion with an international movement analysis software company, the potential limitations of such algorithms for velocity were highlighted and acknowledged. Typically, such camera-based systems are best suited for recording and

analysing continuous and/or rhythmic motion so that start and end-points can be ignored. Such systems have found considerable support in gait and sports analysis which is continuous and essentially periodic in nature, with relatively long data capture times. The end points of movement and the motion around them are crucial to this project so this data cannot be ignored, modified or lost to suit numerical efficiency.

3.2.3 Positional Measurement Devices

The following sections describe common sensors that might be used to obtain positional measurements. Direct measurement of velocity, acceleration and force are not anticipated for the first prototype and hence the technology is not reported here.

Draw-wire sensors - These rely on a pre-tensioned wire on a calibrated spindle connected to an accurate variable resistor. As the wire is pulled from the spindle the resistance changes and a near-linear voltage can be derived which is directly related to the extension of the wire. They are used extensively in the motor and manufacturing industries and are robust, relatively inexpensive and reliable. Direct reading accuracy (before any processing) is typically less than 0.5 mm with good repeatability. They require a fixed connection to a measuring point and each sensor can only measure a single linear dimension or rotation although combinations can be used to measure 3-D movements. The spring force needs to be overcome for measurements to be made and this may affect the measurement itself if it is too large or unbalanced across the measured range. Additionally, the wires may impose some operational or safety limitations as the subject may be exposed to them although they are smooth and largely unreactive.

Linear and Rotary Encoders - Linear and rotary motion data can be derived from a series of counts or pulses from an optical or mechanical switch by knowing the distance or angle that each pulse represents. More sophisticated devices will encode a position as a serial code for direct use by a digital process such as those employed in Grey codes which were patented by Frank Gray in 1953. These devices are robust, being used extensively within manufacturing machinery and are relatively inexpensive. Devices can be absolute or relative and can offer very high resolution, accuracy and precision. However, they require an interface to the point of motion such as a draw-wire and spring, direct acting slider, close-coupled gear or other device. Each of these add complexity of manufacture and potential inaccuracy as noted for draw-wires above.

Optical Measurements - Images from cameras (visible and infra-red) can be processed to provide accurate measurements in 3-D space. The equipment is expensive and requires regular calibration but benefits from not requiring any direct contact with the point of measurement. As a result, no artificial forces or restrictions are imposed on the subject. However, if the points of measurement are obscured or distorted, measurements may be lost or corrupted. For reliable measurements, multiple cameras are required to be set up around the measurement point. Whilst not necessarily intrusive, they require space and cannot be moved without further calibration. Large-scale systems are expensive and require space around the user's working area.

Small-scale systems are typically based upon using infra-red (IR) sensors configured to capture movement within a pre-defined volume as part of a natural user interface (NUI) with PC environments and games. These have been used for gross movement detection on game

consoles such as the Xbox that uses Microsoft's Kinect. More recently smaller volumes and finer movements can be interpreted with devices such as the Leap Motion Controller interface by Leap Motion Inc. Initially for local PC interactions, these devices will become familiar as part of NUIs for all digital devices and are becoming available for developers. The operating envelopes are still small and measurement quality is not declared. Additionally, their primary objective is gesture recognition and the algorithms and signal processing used to interpret these is unknown.

Magnetic Measurements - Measuring the magnetic field around a sensor from a known emitter allows accurate 3-D measurements in a similar way to optical measurements using cameras. In fact both systems are regularly used in motion capture for video and special effects. The advantages of reduced equipment space and self-calibration can be attractive. However, the sensor or a marker needs to be mounted within the measuring space and typically and this may limit the type of interface used.

Cost is still a significant issue for accurate systems although recent low-cost devices for touch-less interaction with mobile media are being reported [175]. Related technologies are in production and will become affordable and will continue to improve in reliability. The limitations associated with unknown data processing and gesture recognition bias noted earlier for optical systems apply equally to these devices.

Inertial Sensors - These systems use gyroscopes and other sensors such as accelerometers to calculate the movement of an attachment point. The data is usually transmitted wirelessly to a controller and acquisition unit. Accuracy can be high but the need to mount the transmitter may have limitations in a rehabilitation environment. Without a constant reference point, measurements can drift and become ambiguous and all measurements are subject to processing algorithms to interpret the signals from the sensors. Errors can be minimised but regular calibration is required. Systems are typically complex and expensive.

PC Mouse - A standard PC mouse houses a usable measuring system which has been successfully used to measure reaching trajectories in normal participants [176] which compared various designs of mouse. Older devices use a rotating ball that acts on two rotary encoders providing X and Y relative displacements. These are very reliable provided the ball remains in contact with the surface and does not slip and/or the housing does not rotate. Most designs now rely upon comparing images captured below the mouse. These are very sophisticated devices relying upon commercial and undisclosed algorithms. They are sensitive to the method of use in much the same way as older devices although slipping is not a concern. However, optical quality of the surface over which the images are compared is important if the inherent accuracy of the mouse is to be realised. Such devices are relative sensors and the data provided may be subject to commercial algorithms that simplify movements although these can be deactivated in sophisticated systems.

Even advanced gaming mouse designs are relatively inexpensive and can provide a low-cost and accurate sensor if it is calibrated and the raw data stream is used prior to any uncontrolled data processing.

3.3 Assessing Potential Parameters

Ideally, the assessment of potential kinematic parameters would be made against an agreed standard that documented typical behaviour for any normal or patient user at any stage of normal development or recovery from injury. Whilst such a collection of performance data is developing and considerable progress has been made in some areas, a comprehensive guide is not available. Hence, most new developments are compared against established, relevant clinical scales as a baseline from which to judge the merit of a new system. There are theories of idealised movement which can be extrapolated to rehabilitation progress such as those described in 2.3.2. Such systems require sophisticated equipment and without this velocity and acceleration parameters cannot be readily extracted from positional and temporal data.

For the proposed ARMaT device, comparison of kinematic parameters with established scales was decided upon at least two such scales were available for all patient participants undergoing a relevant clinical trial into which prototype 1 was included for assessment as noted in section 5.1.

In order that the most valuable parameters were identified, a qualitative assessment of potential parameters extracted from simple positional data provided by this project was carried out and this is summarised in this section 3.3.1. This approach does not preclude adding or amending parameters as they become available and it allows for a structured approach to the design and development of new devices.

Based on in-clinic observations by the author and discussions with clinicians and therapists a basic reasoned assumption was made. It was agreed that simple reaching movements captured at the hand on a 2-D table surface could approximately define the quality of motion of the upper limb howsoever that hand motion was achieved by the user. Such movements needed to present a challenge that should be scalable in different ways. Periodic movements were to be avoided as the results may be influenced by larger body motions such as swaying which would not be helpful in assessing a single limb. If desired movements were captured with sufficient detail, small changes in movement could be indicators of rehabilitation progress. Hence, simple XY movements were planned to be measured on a table top and combinations of the resulting data used to identify potentially useful parameters and possibly a single or compound metric.

3.3.1 Potential Assessment Parameters

Any simple 2-D reaching task can be characterised by the path travelled and the time taken to achieve the task. Figure 3-1 shows the main parameters that could be reliably measured directly or derived from recorded data. These descriptors are used throughout the following text.

The ideal trajectory (IT) is not necessarily the most appropriate for human upper limb movement. As noted in section 2.3.2 normal reaching movements will generally follow a curved path rather than the straight one identified by the IT. Hence, the most appropriate path to follow may change as rehabilitation progresses and this is particularly notable where participants need to use trunk movements to supplement any limitations in their upper limb due to muscle weakness, profound paresis or tremor. The shortest distance was adopted as the

ideal to provide a common baseline for all participants. As greater understanding is reached on the development of preferred pathways, the comparison could be readily adjusted.

Given the positional and temporal data anticipated, a number of derived data sets were considered as potential parameters. Table 3-8 describes absolute parameters derived from the path data described in Figure 3-1. The comments include initial suggestions of relevance based upon preliminary observations of normal and patient participants using a typical PC mouse or similar desktop activity.

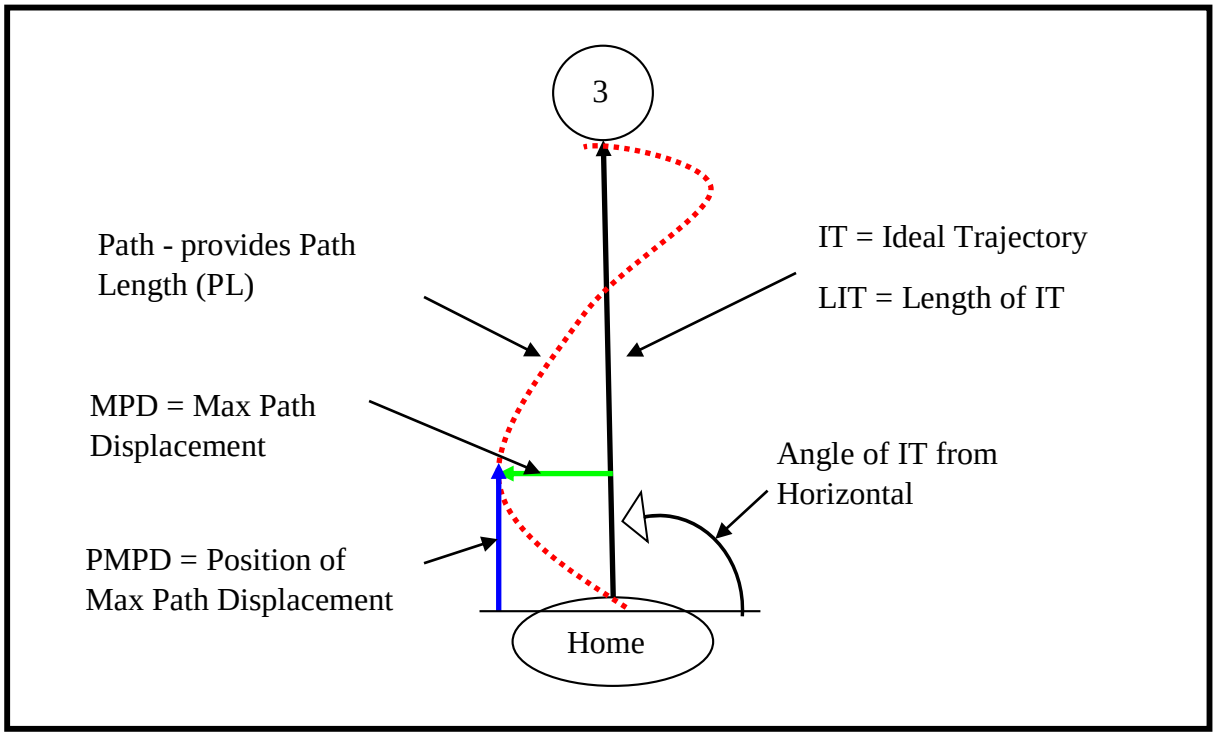


Figure 3-1 Principal Measurements Derived from Raw XY Mouse Data

Further relative parameters are described in Table 3-9. These are considered more robust parameters as they help to eliminate potential scaling errors between the software and hardware. There is a further consideration when using the absolute parameters of path length (PL) and path time (PT) in isolation for the different trajectories. As these may not be identical within a planned activity, the median or average results across a data set would not be comparable between trajectories and sub-groups and hence analysis would need individual comparison for each trajectory and angle.

Values of the parameters such as PL, PT, MPD, DA and MDLoT, and their relative parameters in Table 3-9, that reduce with practise may indicate sensorimotor learning and/or improvements in overall reaching ability. Clearly, there are minimum values below which no participant could progress and these might be established with sufficient testing.

Table 3-8 Summary of Potential Absolute Parameters based on Raw Game Data	
Absolute Parameter	**Commentary** (See Figure 3-1 for explanation of key measurements)
Path Length (PL)	The total distance travelled from the home point until hitting the target. Large values might indicate potential problems in trajectory planning, sensorimotor capability, ability to concentrate and response to physical challenge. The PL can be less than the LIT as the trigger point for reaching the target is a defined overlap (50%) of the mouse cursor and the target icon.
Path Time (PT)	The time taken to move from the home base to the target. Large values indicate potential problems in trajectory planning, sensorimotor capability, ability to concentrate, response to physical challenge, continuity of movement.
Maximum Path Displacement (MPD)	The largest perpendicular distance from the ideal trajectory that the path reaches. Large values may indicate potential problems in trajectory planning, sensorimotor capability, ability to concentrate and/or planned response to physical challenge. Left or right side dominance is predictable in normal participants and given the symmetry of the device and system, any influence from the device can be ignored. Given the natural curved path followed by normal participants, zero displacement would be unusual unless a lower bulk speed were observed.
Displacement Area (DA)	The area described by the path to the left and right of the IT. Areas to the left and right of the trajectory were recorded as well as total (TDA) and nett areas (NDA). A small value of NDA indicates a path that follows similar displacements to either side of the IT. Left or right side dominance, as noted for MPD.
Position of Maximum Path Displacement (PMPD)	The position along the ideal trajectory where MPD occurs. There is evidence to suggest (see section 2.3.2) that the PMPD may identify the peak of a ballistic movement following which fine motor controls are required to reach the target successfully.
Maximum Distance in Length of Travel (MDLoT)	The maximum distance reached in the direction of the IT before hitting a target. This may suggest the accuracy and/or efficiency of a movement with values near the LIT suggesting good planning and control. Large values may indicate significant over-shooting of the target and may be associated with large values of PL and PT.

Table 3-9 Summary of Potential Relative Parameters based on Derived Data	
Relative Parameter	**Commentary** (see Figure 3-1 for additional explanation of terms)
PL / LIT	Normalized measurement for each trajectory to eliminate scaling errors. The ratio of maximum to minimum LIT is important if paths are to be compared for each trajectory. Each movement should ideally require similar stages of planning and execution, involving gross and fine motor control and intrinsic and extrinsic modelling.
PL/PT	A form of bulk speed (BS) for varied path lengths and times. This parameter could represent a measure of movement efficiency or capability to recover position despite an inefficient path. It is possible that this parameter would identify inefficient movements such as those involving larger muscle groups or trunk movements.
PMPD / LIT	Typical trajectories suggest a range from 0.4 to 0.6. Significant increases might indicate poor trajectory planning or overshoot, uncontrolled ballistic initial movements or complete lack of control.
MPD / PL	Similar to MPD alone but eliminating scaling errors for large values of PL which might result from poor control or coordination
MPD / LIT	Similar to MPD alone but eliminating scaling errors Provides a normalized measurement for all similar trajectories.
DA / PL	Identifies the shape of the path by describing a measure of compliance with the desired path. Similarly, deviations to the left or right of the ideal trajectory may identify consistent limitations in body segment use, cognitive ability and control.
MDLoT/LIT	Normalised measurement for each trajectory to eliminate scaling errors.

3.3.2 Comparison of Potential Parameters

Ideally, direct comparisons with other discrete measurements in typical clinical scales would be made so that path length, trajectory, available time, etc, could be identified. For example, in a NHPT, a typical pattern would be to move a peg from one position to a matching position. Hence, peg 1 moves from hole 1 in the starting board to hole 1 in the finishing board, and so on. All trajectories would be similar in length and not dissimilar in angle. Accuracy of planned motion and compliance with a simple rule would be required rather than basic speed trials that require cognitive ability to plan and execute a successive series of movements. However, the patient groups observed with the TPT did not follow (none was imposed upon them either) such a pattern, generally preferring to place the pegs in the next closest hole available and occasionally attempting to remove pegs after placement to allow another peg to be inserted.

For the MUUL/MA2 test, the various arm movements were not particularly similar in nature, nor were they measured directly, so isolated comparisons could not be sensibly made between any assessments.

3.3.3 Pre-selection of Parameters

Within the literature, a large number of potential kinematic parameters were identified and these formed the basis of those noted in Table 3-8 and Table 3-9. Further combinations and permutations of these are possible, and potentially useful, but a large number of potentially very similar parameters is not helpful and is time-consuming to process. Hence, certain potential parameters were pre-selected and this process is described in detail in section 5.1. It is summarised here to offer justification for investigating a wider range of parameters than might be typical from the literature.

As will be discussed in section 3.5 no single parameter was expected to be suitable for assessing ability across all participants. Hence, a combination of parameters appeared to be the most appropriate measure in forming any new metric of ability. Without definitive data for the most appropriate parameters and their combinations for each sub-group, selection processes were used to identify both suitability of the data (normality) and commonality of value or impact between sub-groups.

There are numerous combinations of parameters that might inform a new metric and these might all be assessed. However, pre-selecting a suitable set of parameters from the very large potential number of parameters is more efficient. The parameters in Table 3-10 were chosen by the author based upon initial observations of the data for each sub-group, noting any significant and/or consistent differences between them. This was predominantly a qualitative assessment using limited data from early investigations but is consistent with the kinematic parameters explored in section 2.3.2 and uses the more robust measurements possible from the concept B which is introduced in section 4.3.

The last three parameters were used to identify patterns of handedness rather than real measures of ability. This was considered interesting following early observations of patient participants who were atypically left-handed compared to normal participants. This is discussed in more detail in section 6.1.

Table 3-10 Pre-selection of Potential Parameters for Analysis	
Relative Parameter	**Commentary**
Path Length / Length of Ideal Trajectory (ratio)	Anticipated to indicate capacity to control movement along length of trajectory and to identify path corrections.
Path Length / Path Time (mm/s)	Anticipated to differentiate between careful, slow movements with continuous corrections and well-planned, confident and accurate movements.
Length of Ideal Trajectory / Path Time (mm)	A normalised measure of path time for common assessment across sub-groups.
Maximum Path Displacement / Path Length (ratio)	Measure of control of the path taken related to actual path length which might vary considerably between sub-groups.
Maximum Path Displacement / Length of Ideal Trajectory (ratio)	As above but a common measure of path control between all trajectories.
Total Displaced Area / Length of Ideal Trajectory (mm)	A common measure of path control when following the ideal trajectory.
Total Displaced Area / Path Length (mm)	As above but relative to any path taken and hence a potentially more sensitive measure.
Maximum Distance along line of Trajectory / Length of Ideal Trajectory (ratio)	Anticipated to identify planning and control abilities for any trajectory
Position of Maximum Path Displacement / Length of Ideal Trajectory (ratio)	Anticipated to indicate potential dominant movement phases (gross and fine) as ability improves
Area to Left of Trajectory / Length of Ideal Trajectory (mm)	Indication of tendency of path followed to be to the left side of the trajectory, which may indicate dominant behaviour related to handedness.
Area to Right of Trajectory / Length of Ideal Trajectory (mm)	Indication of tendency of path followed to be to the right side of the trajectory, which may indicate dominant behaviour related to handedness.
Nett Area / Length of Ideal Trajectory(mm)	Indication of tendency of path followed to be to one side of the trajectory, which may indicate dominant behaviour related to handedness.

3.4 Data Capture and Processing

Collecting and storing data systematically allows maximum flexibility when using any pre- or post-processing algorithms which may be needed to help visualise or analyse the raw data. Before any analysis was carried out on the collected data, a decision as to what, if any, pre-processing should be applied to the raw data had to be made. The initial assumption for the data sets gathered was that as much potential content as possible should be preserved. This is generally possible with linear positional data where streams are stable and do not suffer from too much imposed noise; typically achieved by digitising at source before transmission. The rate of data capture should allow sufficiently small steps to be recorded without resorting to any form of interpolation that might mask or corrupt interesting movements or tremors.

Inevitably, there is an issue with the discretisation of any analogue single from the sensors. Many analogue sensors provide a voltage or current signal that represents the desired measurand accurately, there being no corruption of the signal at source. Many signals are scaled to common industry standards such as 0-10V or 4-20mA. This signal is then digitised using an analogue to digital converter (ADC) to allow rapid and predictable manipulation (scaling, transfer, storage, etc,) by digital systems. It is at this conversion point that intrinsic errors are introduced and need to be understood and quantified. The system must be predictable, within known limits, so that subsequent results can be interpreted correctly.

In order to obtain velocity data (direct measurement was not possible with the given solution for concept A, concept B or prototype 1) positional data can be differentiated or acceleration data integrated. As positional data alone was recorded, differentiation was required. Appendix 3B contains a detailed assessment of the types of measurements and errors that can be expected in digitised signals and can be referenced when considering the design limitations noted in the following sections.

3.4.1 Numerical Methods

When differentiating digital signals, numerical methods are required and any limitations in implementing these need to be considered and any resultant errors accounted for. The following sections address these issues as they proved to be a significant limitation in determining viable data for velocity measurements.

A number of important features of sampling real data become evident at the start and end points of a discrete movement. The data presented in appendix 3B to calculate velocity used a backward difference calculation to calculate the change in value of position with each time step, as noted in Equation 3-1. This results in the loss of the first data point, which is undesirable, particularly when short movements result in limited data points being captured. Similarly, if forward differences were used, the last point would be lost.

Of more significance however, is the initial approximation that finite differences provide. Both forward and backward differences are effectively calculating the slope of the curve by assuming a linear approximation between two points. This works well for regular shapes but is unpredictable for complex paths with large Δt as the straight line assumption will be gross and may cross the path rather than offer an approximate tangent to it. Central difference techniques reduce this problem in most cases provided that Δt is sufficiently small to capture

the path shape. The central difference approach effectively fits an approximate quadratic curve to the path and this improves both accuracy and reliability.

Given the above limitations on finite difference methods, a more appropriate method would be to use a forward difference for the first point, a backward difference for the last point and central differences for all intermediate points. Hence, for n equally spaced points (assuming a constant Δt):

$$v_{x0} = (x_1 - x_0)/\Delta t$$

Equation 3-1 Velocity Estimate from Forward Difference

$$v_{xi} = (x_{i+1} - x_{i-1})/2\Delta t$$

Equation 3-2 Velocity Estimate from Central Difference

$$v_{xn} = (x_n - x_{n-1})/\Delta t$$

Equation 3-3 Velocity Estimate from Backward Difference

The assumption of equally spaced time intervals is not necessarily correct and variable intervals can be accommodated by replacing Δt by the respective forward, backward or central difference interval values. This is achieved in MATLAB™ through the use of the "gradient" function. Higher derivatives are possible by applying the same procedure to the first derivative but these are ill-advised because of the truncation and rounding errors, noted in appendix 3B being amplified at each stage.

Noting that the central difference method represents a quadratic fit, an improvement upon this would be a higher order method and this is provided by the Richardson's Extrapolation which is derived from a Taylor series expansion and is summarised in Equation 3-4. There are a number of similar extrapolations in the standard texts which might be employed.

$$v_{xi} = (x_{i-2} - 8x_{i-1} + 8x_{i+1} - x_{i+2})/12\Delta t$$

Equation 3-4 Richardson's Extrapolation of Equally Spaced Data

For higher derivatives of equally spaced data, this becomes:

$$a_{xi} = (x_{i+1} - 2x_i + x_{i-1})/\Delta t^2$$

Equation 3-5 Richardson's Extrapolation for Acceleration

Even when the sample amplitude is large compared with the ADC resolution, the errors can still be unacceptable when numerically differentiating real data. As the signal passes through a zero point the value of the sample may be extremely small but the ADC may adopt a discrete value other than zero. This is indicted in appendix 3B which shows that the true position may be a very small displacement but the ADC may propose a value of ± 0.12mm.

There can be rounding errors within mathematical engines which, although small due to the resolution of the computer, can be compounded when multiple calculations are involved.

These cannot be evaluated readily and are assumed to be small given the much greater resolution in a standard PC mathematical engine compared to the 12 bit ADC noted in appendix 3B.

Using the data from preceding calculations, the resultant velocity (speed and angle) are given by:

$$v_n = \sqrt{x_n^2 + y_n^2}$$

Equation 3-6 Resultant Speed from X and Y Velocities

$$\alpha = \tan^{-1}\left({}^{v_y}/_{v_x}\right)$$

Equation 3-7 Resultant Angle from X and Y Velocities

The choice of method for appropriate differentiation has proved to be a significant issue for the type of data gathered from simple reaching movements. A number of issues have been recognised which preclude the use of simple analysis and regression techniques. These are identified below:

Non-periodic - The data is typically a single movement and there is a reasonable assumption that the start and end points are important and should not be lost or mutated. This precludes techniques which rely upon underlying trends which can be reinforced with repeated measurement such as running, rotational exercises or fixed axis machines. Even repeated identical reaching movements rarely start and end at the same point and hence dependence upon simplifications for efficient analysis is inappropriate.

Non-continuous - The data for normal participants will typically show a continuous predictable displacement in both X and Y movements with time, which could be modelled with polynomial equations. This would simplify differentiation to obtain continuous velocity profiles. However, patient participants display re-entrant paths and repeated attempts to reach targets via different paths. This data cannot be regressed using continuous functions such as those used to assess projectile behaviour and fixed path force-feedback motions. Similarly, discrete reaching movements with a pause between targets are inherently discontinuous.

Uniform time-series - As measurements are derived from an electronic timer or clock, the time interval Δt is not always uniform, or it is not reported as being uniform. This is unavoidable and has been seen to distort the derived velocities along the path. This was addressed by other researches by resampling the data to an equivalent equal time-step [77] thus permitting a symmetrical moving window to obtain the local velocity.

3.4.2 Noise in Sampled Data

The various calculation errors, truncation errors and sampling errors noted appendix 3B and inevitable physical measurement errors can significantly distort data. Hence, there is a considerable and largely unquantifiable issue with data integrity from measured and differentiated positional signals. This could be thought of as noise overlaid upon the basic true signal that is required from to be measured. To this must be added the vagaries of human motion which is initiated and maintained by an inherently noisy system, the SCS.

It is important to identify what might be termed signal processing system (SPS) noise from SCS noise. The method of dealing with noise might be similar. However, the SPS noise is unwanted whilst the SCS noise may hold important information about rehabilitation progress and this should not be disguised or discarded without full knowledge of the method and effects.

Typically, noise can be extracted or smoothed by applying filters which either ignore certain frequencies or signals or which average unwanted peaks into adjacent points. Both processes are well documented for periodic signals such as acoustics or machine dynamics. Well-established passive and active filters exist which clean up the signal at source or later during digital post-processing. Within the biomechanics literature a number of techniques are commonly used although their specific effects on the data is rarely described nor are the boundary effects noted.

The most commonly used filters are Butterworth and Savitsky-Golay, both of which address the frequency of unwanted noise to be suppressed or removed. The Savitsky-Golay filter operates as a form of weighted moving average filter, effectively fitting a polynomial curve to a window of data on the path. The Butterworth filter is typically used in audio circuits to return equal amplitudes at all frequencies in the desired pass band and can take various orders to improve this response.

In their paper, Ahnert and Abel [177] describe the *"shortcomings"* of local and global methods and offer potential solutions for numerical differentiation using consistent measures of accuracy and smoothness. Local methods include finite difference techniques and the Savitzky-Golay method described earlier, which rely upon a local estimate, typically using a moving window on a small set of data. In contrast, global methods such as smoothing splines, address a wider selection of data points using a least squares approach to fit a curve along all points rather than basic interpolation over a limited window of points.

There are limits to the conclusions that Ahnert and Abel offer for their comparison of known (sine function, Lorenz system) and unknown (sampled acoustic data) functions. They assume an equi-spaced interval, for example a constantΔt, in order that their methods can be compared and processed efficiently. However, the main conclusions can be used as a guide for the numerical differentiation required in this project and these are summarised in Table 3-11. For the type of data expected smoothing splines are the preferred choice, yielding the best fit for a non-periodic function and best smoothness with good accuracy. The issue of non-continuous data and variable time step is not addressed by using smoothing splines and the discontinuity noted with sudden or rapid changes of direction cannot be accommodated by using splines.

In conclusion, it is unlikely that reliable and meaningful estimates of velocity and hence acceleration can be obtained from positional data alone. It is possible, however, that using suitable readily available accelerometers, could allow acceleration and an estimate of velocity to be obtained by numerical integration. Integration is a more stable numerical method although accelerometers are inherently noisy and will require careful treatment and filtering to maintain movement integrity.

Table 3-11 Comparison of Numerial Differentiation Methods			
Parameter	**Global - smoothing splines (SS) and spectral estimators (SSE)**	**Local - finite difference (FD) and Savitzky-Golay (SG)**	**Remarks**
Smoothness	Best	SG orders of magnitude away from SS ad SSE	A second differential used to assess curvature
Speed and simplicity of calculations	Acceptable with smaller data sets (less than 10000)	Best	Numerical cost
Response to added noise	SS best for high noise, SSE for low noise content. Both better than SG	FD orders of magnitude worse, dismissed as a method	Results of adding white noise to known functions
High-precision	Best	Variable	An accurate calculation from known derivatives
Least-squares error	Similar to SG	FD dismissed	A measure of fit for the assumed function
Non-periodicity	SSE best for periodic functions, SS best for non-periodic functions		Discussed earlier
Higher differentials	Effective	FD requires additional smoothing and yields large errors	Stability when calculating repeated differentials (position to velocity to acceleration to jerk)
Variable time interval	Not specifically addressed	FD manages this well	Discussed earlier
Preserving end points	SS smooth, SSE grossly distorted	SG adequate but some distortion, FD not used	Assessed for differentiated acoustic signal

3.5 Statistics used in Measuring Human Performance

In investigating the use of statistics to support and interpret the many observations made in this project, the author has encountered a variety of theories and practices. Whilst diverse in their application, most have their origins in engineering or physical science, being methods for determining trends and responses to known and planned changes in processes. How to apply these techniques both appropriately and successfully requires an understanding of how and why they were developed and what their limitations were when they were first conceived or subsequently revised. These limitations remain largely unchanged despite advances in analytical techniques and mass data manipulation. The background to all of the statistics used in this project are contain in the help files of SPSS™ [178]. A summary is included in this chapter to support understanding the results reported in chapter 5 and discussion in chapter 6.

Statistics may be complex in their application though relatively simple in their formulation and software such as MSExcel™, SPSS™ and Minitab™ exist for manipulating the data. However, the more diverse or complex the data or method of collection, the more difficult it is to agree upon the most appropriate method to use. Basic statistical approaches help to interpret, not decide, the differences between sets of data whether they be measurements of engineered components (the diameter of a sample of bolts from two machines) or measurements of human response or behaviour such as the distance that a subject moves their arm in a reaching task before and after therapy.

3.5.1 Engineering and Biological Data

Engineered components are predictably simple and obey well-defined rules, most of which are measurable against a standard. Manufacturers may wish to ensure that the component (bolts in this example) fit whatever they are designed to work with. If the sample chosen is representative of the whole production run then a good sample will infer that the whole batch can be delivered as being compliant. Some may not be and may not fit well but the chances of those are small or can be made small depending upon the application. There is a quantifiable risk that so many bolts will not fit properly. As it is relatively easy to pick out another bolt, there is only a commercial risk that the customer will be dissatisfied. If the sample suggests degrading manufacture then the machines can be examined, measured and adjusted to rectify the fault. This is the basis of the majority of statistical approaches that were originally developed for assessment of agricultural growing conditions by Sir Ronald Aylmer Fisher (1890-1962) who is considered by many to be the "father of statistics". The data being assessed is typically simple to understand, predictable in distribution and repeatable within known limits.

Measuring human performance can be considered in a similar way to measuring parameters of engineered components. Groups of subjects (patients with an arm affected by ABI, in this example) can be compared based on simple measurements such as their time to reach a target (path time) or the distance travelled (path length) when measured in a standard setting. One group may perform notably better when compared to another. If different therapy systems were used between groups and the groups were large enough, it could be inferred that one therapy is better than another if a significant difference in score (path length or time) was recorded. However, humans are very noisy subjects to measure when compared with simple engineered components. Whilst it can be argued that groups of humans may come from a

normally distributed population, the reaching abilities of small groups and particularly those with ABIs is arguably a less reliable sample than bolt diameters. Hence, different statistical methods may need to be applied. However, the different methods all have limitations. The more simple and predictable the problem and measurement, the more reliable the inference from the statistics used. The more complex or unpredictable that the measurements and subjects are, requires far greater care and the use of any statistical process should be approached with caution.

As the author reviewed the literature it became evident that some statistical analyses were questionable even if the experimental method and data capture were sensible and rigorous. Potentially inappropriate techniques were used to analyse data that was unlikely to meet the conditions stated for that technique to be reliably applied. As a consequence, the analysis of data became a significant area of work within this project. Rather than just relying upon the "normal process" or "house-styles" adopted by others, a thorough review of the techniques was conducted. The measurements in this project are deliberately simple and understandable. It would be unacceptable to cloud their meaning with unpredictable or questionable statistical inferences.

3.5.2 Comparison of Data types

Key to understanding how to gather and process data effectively is to understand what types of data exist and then how they should be treated to provide reliable support or otherwise to an investigation. For any therapy or drug trials, an outcome is anticipated as a result of some intervention and this needs to be investigated and tested to see if it is effective, or "true". This could be a simple hypothesis such as "more physiotherapy is better," or "by using this therapy, motor function will be improved". Important to both of these assumptions is to know:

- What is being measured - speed of response, dexterity, balance, etc.?
- Are the measurements meaningful to the assessment - do the parameters truly reflect movement ability in a reaching task?
- What is the starting point for the subject or group - does a reliable test exist for what is being measured?
- Any special requirement to isolate the therapy from other activities that may affect the test – for example should the upper body be restrained in a specific reaching task to limit trunk movement?
- Are the measurements repeatable and readily measured/recorded - can reasonably accurate measurements be made during the same test with different subjects, addressing their individual needs, using a single therapist or device?
- How is the bias or influence of the therapist accounted for? A therapist's determination to help a subject can be extremely influential in assessing performance.
- Do the subjects know what is being attempted – will this influence their performance?
- What is the therapy anticipated to achieve - is the test a real challenge of ability - is it sufficiently difficult to exercise the ability of all that are tested - could some subjects never achieve a consistent standard or over-achieve too quickly (floor and ceiling effects)?

Testing human performance can be extremely challenging. Response to, or performance within, a simple task (reaching for a cup, for example) can involve so many seemingly unrelated conditions as well as those that are more obvious. Some of the obvious conditions might be:

- Cognitive ability - can the subject understand the requirements?
- The subjects attitude to the test - are they supportive or hostile?
- The test environment - even welcoming environments may affect people differently.
- The time of the test – attitude and performance before or after a meal, or following medication, can be significantly different.
- Subject's general health - tiredness or excitability could yield markedly different results.
- The relationship between the subject and therapist - repeated testing allows time for a relationship to develop – this may be positive or negative.

Some of the potentially less obvious conditions might be:

- Previous subject experiences (disclosed or undisclosed) - good or bad, these will influence a subject's attitude and hence performance.
- Expectations of subjects and carer - preconceived ideas of the test and how to perform it may overstimulate or dissuade a subject.
- Embarrassment or self-consciousness - some tasks are obviously simple but may be nearly impossible to achieve at first.
- Eyesight - can the subject actually see the equipment or set-up properly.

There are many more and the above list only serves to illustrate the point that each of these conditions may influence the outcome to some degree, even if they could be strictly controlled. As most of these are never addressed consistently (a therapist will try to put a subject at ease if their nervousness is obvious but is unlikely to assess their eyesight) they cannot be eliminated from any potential results.

3.5.3 The Statistical Hypothesis

In order to compare differences between subjects or tests requires suitable hypotheses to explore, a meaningful test and measurement system, sufficient and relevant subjects, raw data and a method to assess or analyse it appropriately. The method of testing and the justification for this has been outlined in this chapter and the measurement system will be developed in chapter 4. The number of participants and their classification is documented in section 5.2 and is sufficient for the level of investigation here, although more participants and further testing would increase the power of the data gathered.

The working hypothesis for this thesis, as stated in chapter 1, is reproduced below:

> ***"Simple movement parameters, obtained from varied but repeatable two-dimensional reaching tasks, can be used to establish a state of rehabilitation from which quantifiable measurements can be made to record progress."***

This is a multi-faceted argument and cannot be used as the basis of a null hypothesis for statistical analysis. Hence, the following is proposed as an extraction from the working hypothesis:

> ***"Movement parameters do not reflect reaching ability of normal and patient participants or between states of rehabilitation for the same participant."***

If the null hypothesis is not supported by statistical analyses then the alternative hypothesis is supported and likely to be generally applicable within the known participant sub-groups:

> ***"Movement parameters can differentiate between normal and patient participants or between states of rehabilitation for the same participant."***

If this alternative statistical hypothesis can be supported then the working hypothesis is also supported.

In order to assess the value of a new metric the statistical null hypothesis noted above can be used once a metric has been established. It was not anticipated that a single parameter would be suitable as a new metric and hence a composite metric would be required to cover the range of abilities in the participant sub-groups.

Assessments were made to determine if any particular parameter provided sufficient support for adoption as a metric in itself or as a component in a composite metric. These assessments were based upon correlations with the Tyneside Peg Test (TPT), the only clinical scale which was common to all participants. From this a further null hypothesis can be proposed such that each parameter or metric can be assessed against another set of data:

> ***"Movement parameters or combination metrics do not correlate with clinical scales and hence do not reflect states of ability"***

If useful correlations are identified then the alternative hypothesis can be adopted:

> ***"Movement parameters or combination metrics do correlate with clinical scales and hence reflect states of ability"***

Again, if the above alternative hypothesis is likely, the alternative statistical hypothesis noted earlier is also supported and the main hypothesis is likewise supported.

3.5.4 Statistical Methodology

Statistics can be used to support acceptance or rejection of the null hypothesis. As such, any conclusions drawn are only indicators of likelihood. The more data sets that can be acquired and the greater the isolation of collateral factors, the more value can be placed upon the calculated statistics. In this project, the number of participants was limited but it was sufficient to provide early indication of useful parameters and a potential new metric. Further participant testing with more sophisticated measurements could provide greater confidence in the proposed metric or further metrics. The statistical methodology used is described in section 5.1.

3.6 Planned ARMaT Development

There are two basic types of devices in use or under development to support rehabilitation of the upper limb; passive and active. Historically, passive systems offering a repeatable challenge based on established PT/OT regimes were used with significant effect and this was discussed in considerable depth in section 2.4. By their very nature, they are limited in application – a rotating or oscillating handle, for example – and cannot be readily adapted to offer varied challenges to users. As such, there is limited scope and opportunity for scaling exercises, developing new or complex movements, introducing real-time challenges or working within variable VREs.

The potential to support more involved therapy processes and to gather subtle as well as gross movements is only available in more sophisticated and possibly active devices. The most advanced devices are typically based upon some form of haptic interface as discussed in section 2.7. The potential for haptic devices to move patients into an immersive environment and to mimic the actions of therapists has encouraged significant development of small-scale robotic devices. This continues with considerable interest and investment and necessary standards to define how to measure and maximise the potential of these sophisticated devices have are being developed. The emphasis in this thesis is on measurement rather than therapy although, as was noted in section 2.5, measurement requires movement which can be therapeutic.

Any new device requires a number of stages to be completed in order to demonstrate that it is feasible, practical and meets the stated requirements. In this project two concept devices (A and B) and a laboratory device - prototype 1 - were used, with plans to develop a clinical device (prototype 2) based upon the conclusions of this project. The detailed design development of prototype 1 is described in chapter 4.

Concept A
This device provided early baseline assessment of a haptic system based on Cartesian axes with a basic VRE. It was intended to establish the feasibility of an affordable modular design using standard stepper motors, simple load measurements and a desktop PC as a common controller and VRE interface. The device showed promise and it provided an insight into how such a system might be used with patient and normal participants. It also helped to identify technical limitations in use, concerns by clinical staff, and improved understanding of the rehabilitation processes being investigated.

Concept B
As concept A could not be assessed under any known medical or commercial standard and no agreed objective measures could be identified, a second proof of concept device was required. Concept B was used for laboratory assessment and limited testing on normal participants to establish suitable measurands. This device provided simple kinematic data using standard desktop PC hardware and software. This non-haptic device was based on PC mouse data with simple exercises in a basic VRE. It established the potential for kinematic data to be used as indicators of rehabilitation progress in real-time.

Prototype 1
Planned to be used for laboratory testing with normal and patient groups, this device built upon the successful elements of concept B. A standard mouse was used as a positional sensor and housed in a suitable frame on a low friction surface supported by a low tension field formed from four springs. This was required to centre the mouse and prevent unplanned rotations that were noted with concept B.

Prototype 2 - Future Work
To be developed from prototype 1 having established the validity of the measurements and parameters against clinical scales. Hardware and software would be revised substantially to improve reliability and provide an interesting and flexible VRE. Further sensors might be added - such as accelerometers and potentially gyroscopes or other non-contact sensors - to enhance positional measurements. Potentially, this device might become a wireless sensor operating in a remote measurement field.

Initial and Potential VRE
In order to limit any contamination of the measured data from complex interactions with a complex VRE, a very simple fan-game was planned which required the user to move from a common base to targets. This had been used in previous devices, as noted in chapter 2, and mimicked simple desktop reaching tasks. The objective was to provide an achievable but non-trivial challenge which would be engaging for all users.

Where useful parameters could be identified in a simple fan-game, it was possible that more information about movement and refinement of parameters would be possible with more complex games. These could be introduced with prototype 2, together with a more flexible interface to create different movement patterns based upon the same concept of moving to targets that appear without prior knowledge.

3.7 Chapter Summary

This chapter has identified the potential application for a new ARMaT device based upon a significant number of potential beneficiaries globally. The methodology proposed provides a reproducible framework to develop a new ARMaT system including functionality and cost limits to potentially deliver measurements of rehabilitation.

Suitable movement parameters derived from positional and temporal data have been identified which might indicate and support the assessment of rehabilitation of the upper limb. Limitations with measuring human performance and the interactions with mechanical systems have been identified and proposals for minimising their effects have been documented. Limitations in capturing, recording and post-processing real-time datasets were explored and suitable methods determined.

Statistical hypotheses in support of the main hypothesis was established for use with the processed data from prototype 1.

A developmental roadmap was identified for the design and implementation of conceptual test beds, a clinical trial prototype and future pre-production prototypes to expand upon this current research.

4 Design Development

As noted in section 1.3, one of the original objectives of this thesis was to create and develop an affordable haptic device that would provide force feedback and additional challenges to users. It was anticipated that this would provoke the wider development and deployment of ART devices. However, some fundamental problems existed that were not immediately apparent and these are applicable to the development of any ART or ARMaT device. Namely, what exercise or therapy regime would be the most appropriate at any stage of rehabilitation and how could the merit of any new therapy be consistently measured? Whilst normal movement is well documented, see section 2.3.2, that for rehabilitating subjects is not so clearly identifiable, nor sufficiently codified to allow simple translation into a new measuring device.

In section 2.2 the applications and need for a new ARMaT device were identified and existing devices and systems based upon haptics were introduced in section 2.7. Potential movement parameters were investigated in section 3.3 in order to identify what measurements any new ARMaT device should be capable of. Similarly, the process of developing a need into a functioning device was presented in section 3.6 following established iterative design-make-evaluate principles.

In this chapter the design and development of a new ARMaT device is described and a series of devices presented which meet the biological needs and engineering processes discussed in previous chapters.

4.1 Performance Specification

In order to select the most appropriate designs from the many potential solutions available and evident in the literature, a performance specification was identified to guide the design development. This was based upon the data presented in chapter 2 and common design approaches for human machine interfaces such as joysticks and other common objects.

Design is a somewhat subjective activity and any design solution can be challenged based upon the opinion of the designers and stated requirements. Indeed, the requirements themselves are rarely defined so closely as to evade questioning. In the development of a new product there is always room for reviewing a solution and overly constrained requirements should be avoided. Hence, the following performance specification is offered as a guide that was used to inform decision-making processes that led to the design of concept B and prototype 1. It is also a valid reference for the development of future devices as noted in section 3.6 for prototype 2.

The performance specification is summarised in Table 4-1. All suggested requirements are provisional and may be modified to accommodate performance or features that might prove beneficial to the development of the device. The sections noted provide additional background and/or justification for the suggested performance criteria.

The following sections provide additional discussion and review of relevant design criteria and potential solutions.

Table 4-1 Performance Specification for New ARMaT Device		
Requirement	**Remarks**	**Design Basis**
Planned type of activity	Desk-top planar motion (2-D). Typical reaching tasks representative of ADLs where possible. Subject to direct device without imposed forces or drives.	Section 2.4.5
Users	Normal and patient participants; typically juvenile although use by adults to be accommodated. Participants typically ambulant and not requiring elaborate support or medical intervention during sessions. Patient group typically hemiplegic CP juveniles; should be applicable to other participant groups.	Section 3.1 Section 5.1 Section 2.2
Application	Provide symmetrical assessment of left and right upper limbs from a seated position. Movements to be unrestricted within the operating envelope.	Section 4.4.1
Usability	System to be simple to use and engaging for participants	Section 4.3.5
Operating envelope	2-D reaching tasks to extend up to 200 mm	Section 2.3
Working surface	Area over which reaching tasks take place: typically 500 mm x 500 mm.	Section 4.1
Space requirement	Maximum space occupied to be consistent with desktop operation. Working plane to be horizontal; nominally 600 mm x 600 mm in plan and 400 mm high.	Section 2.4 and 2.7
Mechanical interface	User provided with a suitable “handle” to facilitate movement of measuring interface or sensors. Patients with limited grip capability to be accommodated.	Section 4.3.3
Sensory experience	Participants to experience representative sensory feedback with all interfaces. The user VRE to promote reaching tasks and provide audio-visual feedback on movements in real-time.	Section 2.6 Section 4.3.5
Friction	Designed to minimise friction and maximise smooth motion; no adverse effect on planned movements.	Section 4.3.5
Inertia	Minimise in design as noted for friction. Future adaptations may provide additional challenges.	Section 4.3 Section 7.2
Measurements	Requires measurement and storage of position and time data during reaching tasks. Data to be stored securely and identified by user code.	Section 3.2
Range	Position: +/- 200mm. Time: 0 - 600 s per task	
Accuracy	Position: 1.0 mm. Time: 0.1 secs	
Resolution	Position: 0.5 mm. Time: 0.05 secs	
Management	Therapist/carer interface for establishing suitable reaching tasks and gathering movement data.	Section 4.3

Weight	Single able-bodied operator set-up on suitable desk or table. System to be readily moved with lighter components forming a heavier assembly if required. No component to exceed 100N.	Section 3.1
Drives (haptic capability)	Not required with passive system but design should not preclude future adaptation or development.	Section 2.7
Components	Maximise use of standard and modular components to minimise cost and complexity	Section 4.1.2
Reliability	Design life of two years domestic use. Measurements to be verified and calibrated without undisclosed screening or manipulation (smoothing, etc,) by commercial interfaces.	Section 3.2.1
Safety	All elements to be inherently safe or limited to safe operation by design. Device to represent no greater risk to a user than any common desktop task.	Section 4.4
Cost	Affordable to domestic users with an indicative cost of manufacturing below £1000.	Section 3.1.2
Sustainability	Design for use of sustainable materials and processes and to permit recycling where possible	

4.1.1 System Requirements

The aim of this section is to identify and present data which will inform the development of ARMaT interfaces both within this research project and for the benefit of any future design. This data will also serve as a reference which may be updated to maintain a current picture of activities and developments in this field without the need for repeated data searches.

The diagram in Figure 4-1 illustrates the key components of a haptic ART device. Not all established systems investigated in this chapter contain all of these elements nor have they all been developed to the same level of sophistication. However, this provides a simple overview of the components that may need to be considered in the planning and design of a new system.

For illustration, the ARMaT device developed in this thesis contains a sub-set (circled elements in Figure 4-1) of those required for full haptic ART, namely:

- Exercise and Session Data Storage
- Central Processor
- Mechanical Linkages or Connections
- Human to VRE interface
- Human to Mechanism Interface
- Human to Controller Interface.

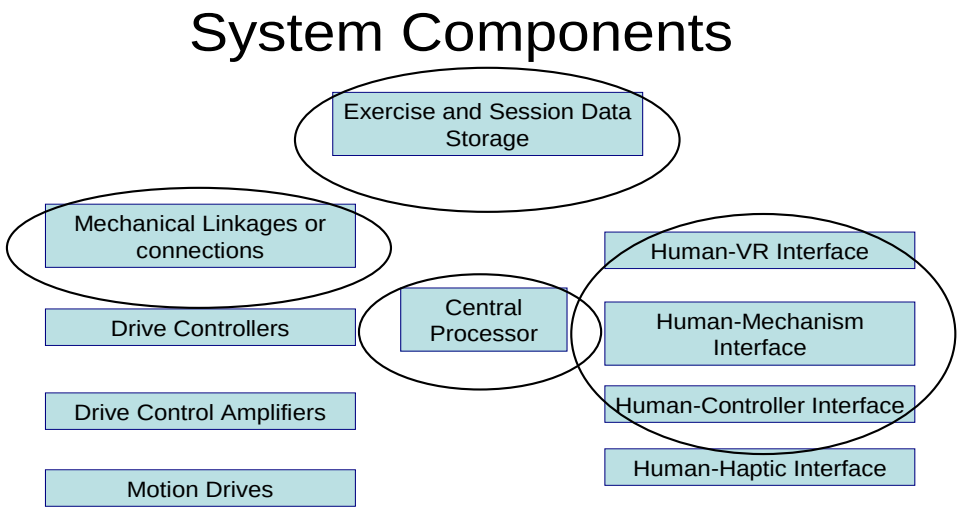


Figure 4-1 System Components for a Functional Haptic ART Device.

The following sections describe and compare a variety of potential arrangements that could be used to provide ART and ARMaT capability. In order to move a selected body segment or segments, a mechanism is usually employed which isolates the required segments and facilitates the required motion paths. This can vary from simple fixed geometry linkages with a single degree of freedom (1 DOF), such as a crank handle or slider, to complex 3-D robot arms with 6 DOFs. Typically, cost and complexity increase with increasing degrees of freedom and sophistication of the associated VRE.

The following images show the principles of generic systems. Some designs are quite specific but most fall into six basic categories and Table 4-2 summarises these with some relevant references for background review. Many of the systems are capable of exerting considerable forces but smaller and less powerful devices are also possible. Although some systems may not be capable of moving a limb, these systems can provide some guidance to users and valuable kinematic and dynamic parameters for assessment, though typically over a limited range of motion.

Table 4-2 Categorisation of Device and Mechansims Employed

Category	References	Remarks
Cartesian Arm	[143]	Figure 4-2
Mouse/skate	[37, 69, 140]	Figure 4-4
Robot Arm	[12, 29, 124, 146, 179, 180]	Figure 4-3
Mechanical Linkages	[23, 89, 96, 142, 144, 145]	Figure 4-5
Polar Arm or wheel	[25]	Figure 4-6, Figure 4-7
Light haptic arm	[91]	Commercial force-feedback device
Wheel	[25]	Bespoke force-feedback device
Joystick	[51, 181]	Commercial force-feedback device

The data in Table 4-2 was used to support a selection process, as described in section 4.1.4, to establish the design basis for the concept B device and subsequently prototype 1.

4.1.2 Categories of ART Mechanism

The following figures illustrate the basic arrangements of existing and potential haptic devices scaled to a nominal working area of 500 mm x 500 mm, being a typical desktop workspace for the new ARMaT. The first, shown in Figure 4-2, is a simple Cartesian arrangement based upon XY coordinates. This has the advantage of simplicity and robustness but occupies a large space, contains large moving parts and potential safety issues with pinch points. It is readily scalable and can be enhanced for additional strength, if required. Adaption to 3-D is possible with the addition of a driven vertical column but this would require further supports to maintain rigidity and stability. This design was used as the basis for the concept A device described in section 3.6.

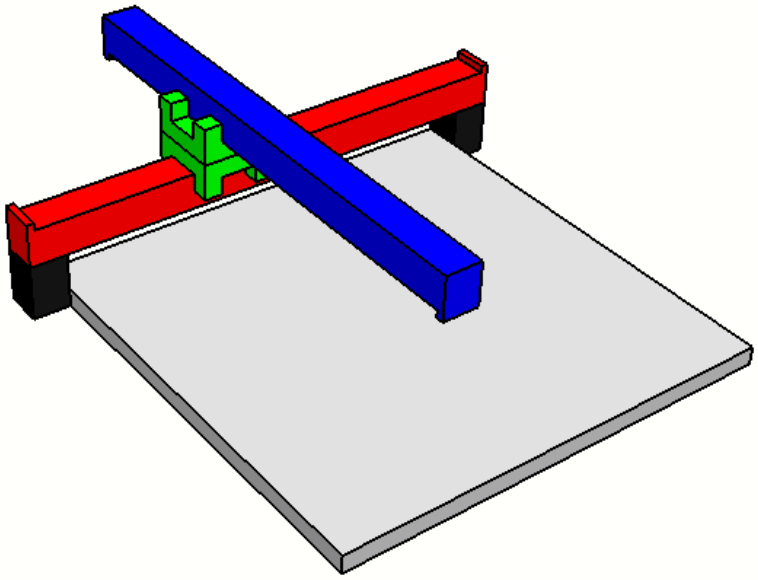


Figure 4-2 Cartesian Arm (2-D)

The skate arrangement in Figure 4-4 relies on maintaining a constant tension or length in the three strings to fix a position. By adjusting the tension/length of the strings the handle above the skate can be moved in the desired direction, although the positional sensors and drives need to be mapped to account for the string angles. This is a simple modular concept with few exposed components and limited opportunity for safety issues to arise.

The drive and sensor systems need to be protected from the user and the environment. This arrangement is also representative of using a mouse or joystick as an interface/sensor although there are limitations with both as described in section 2.6. Adaptation to 3-D is possible using a simple vertical column but is limited as the overturning moment of such a column is significant. A derivative of this device was used for the concept B device and prototype 1.

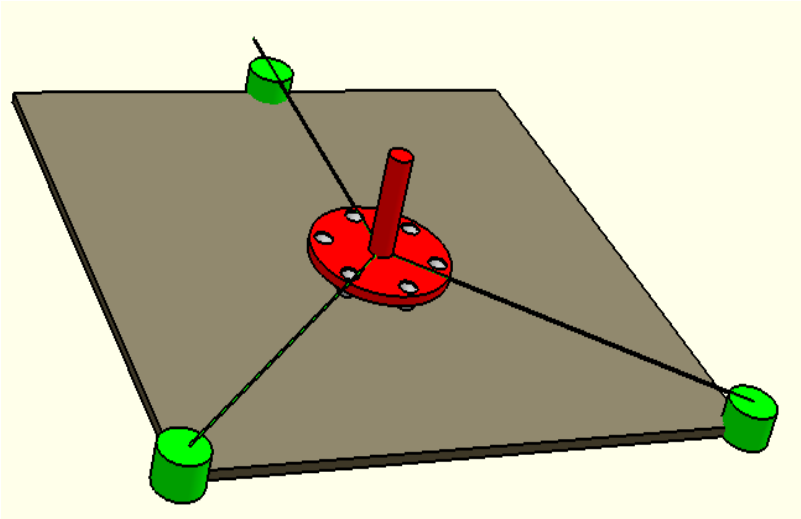


Figure 4-4 Skate in tension field (2-D)

The arrangement in Figure 4-3 is typical of the FCS Haptic Master™ robot. It uses a fixed heavy weight column base, rising stem and extending arm. The mechanism is inherently stiff and positional accuracy is very high. The large size and weight, combined with the significant costs suggest that this approach would be poorly suited for mass deployment. Safety issues need to be addressed as the potential forces involved in moving a body segment with such a device are significant.

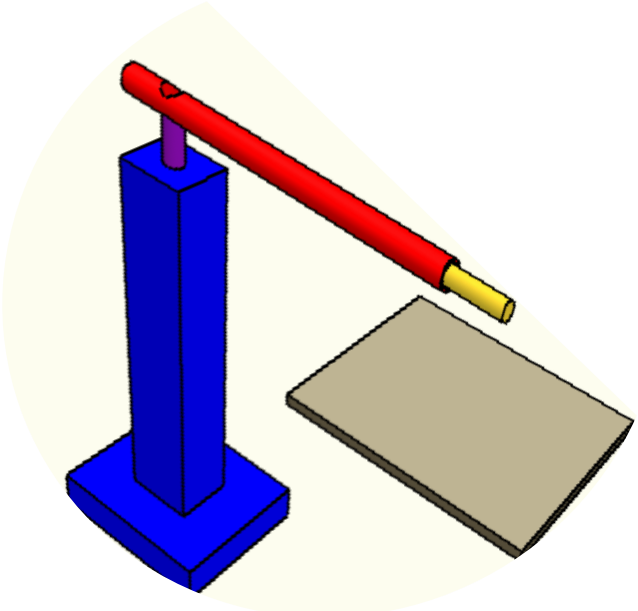


Figure 4-3 Polar Arm (3-D)

The design solution in Figure 4-6 is a simplification of that shown in Figure 4-3, relying on being table mounted and possibly limited to 2-D planar tasks. It has the potential to operate in three dimensions and considerable loads can be accepted at the end effector due to the stiffness and constraint provided by the substantial mounting point and load bearing skate.

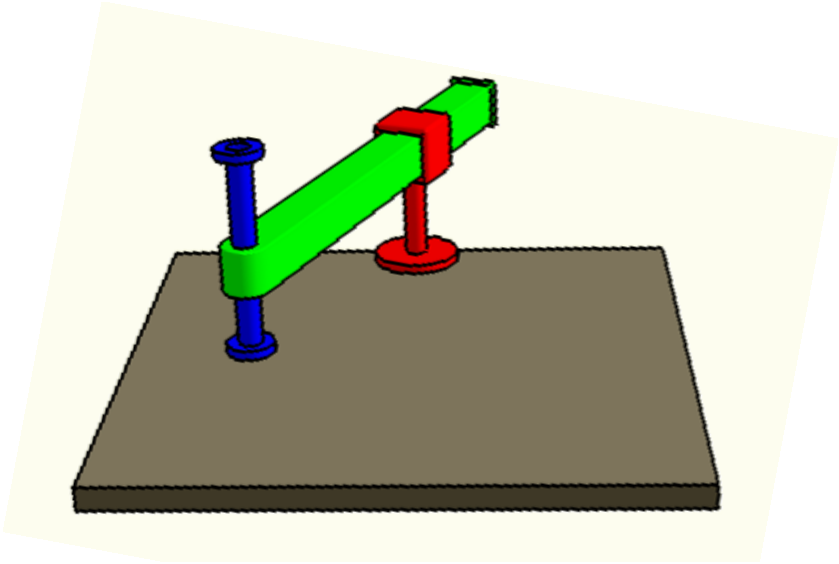


Figure 4-6 Heavy Polar Arm (3-D)

The mechanism illustrated in Figure 4-5 employs a framework with directly connected drives. In this design, the weight of the user's arm is taken through a skate onto a low friction table surface. Most of the components are robust and all are mounted above the table surface.

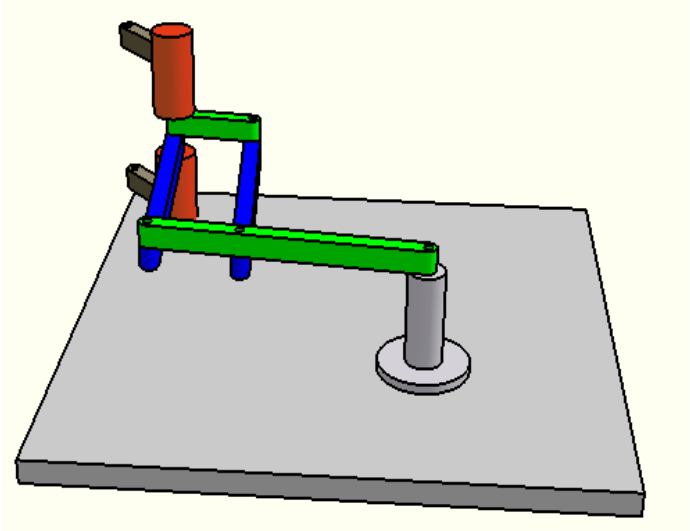


Figure 4-5 Mechanical Linkages (2-D)

This arrangement has high stiffness and benefits from some modularity. The basic system illustrated allows only limited hand grasp locations and these in an orientation that may not be comfortable for users with impaired grip. This could be modified with an extended end effecter although over-turning moments would require a much larger base skate. Adaption to 3-D using an under-hung driven vertical column is possible but unlikely to be viable.

Although considerably enhanced to permit the weight of a patient's arm to be carried without a table, this device is representative of the commercial offering by InMotion™ described in section 2.5. This design offers a robust solution but has an inherent requirement to be an active system due to the mass and stiffness of the linkages. An alternative solution is shown in the light rotating arm in Figure 4-7. This has a reduced weight bearing capacity and potential

applied force and is unlikely to be adapted to 3-D but which might serve as a proof of concept for 2-D applications.

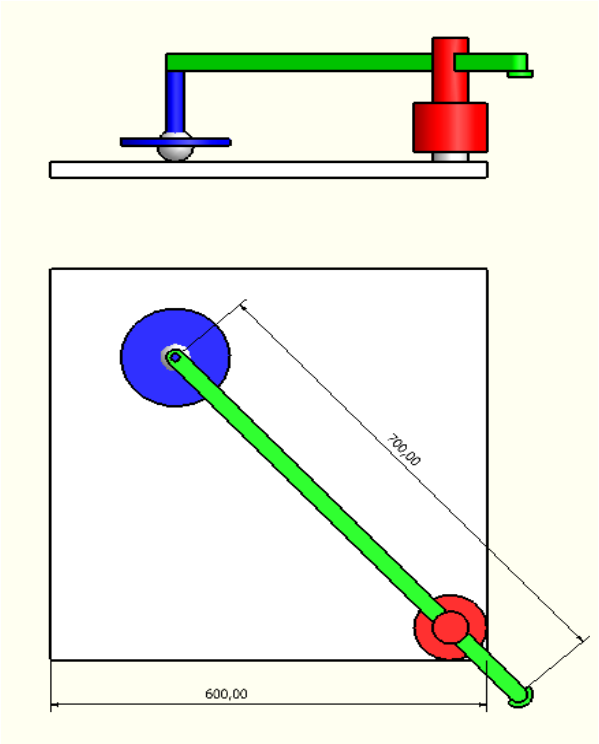


Figure 4-7 Light Rotating Arm (2-D)

Whilst all of these arrangements could be used for a new ARMaT, the objectives of simplicity and affordability established in chapter 1 indicate that the most appropriate are probably limited to a skate based design (Figure 4-4), simple 2-D mechanical linkage (Figure 4-5) or light rotating arm (Figure 4-7).

4.1.3 Designing Effective Affordable Devices

In order for an ARMaT device to be of value to the chosen juvenile participants there are two basic criteria which it must address and should be considered as part of the design specification. The therapy must be measurably beneficial the patient must be willing to participate. Whilst simply stated, these criteria are very difficult to address individually and this is compounded when trying to meet both together. Assuming that a system can be developed to meet these criteria, the following questions are useful in developing any component or complete system and form part of the performance specification noted in Table 4-1, albeit in less precise terms:

- Does the patient enjoy the most beneficial therapy?
- How can the patient, carer, therapist and clinician observe and record progress?
- What will a patient tolerate and for how long?
- How much “non-therapeutic play” can be accepted by the therapist and clinician?
- Is “non-therapeutic play” detrimental to short or long-term rehabilitation?
- What happens when the patient leaves hospital?
- Can carers continue the therapy at home?

Although the present system is not intended to be a haptic ARMaT, the design should be developed to include many of the features required by haptic devices and hence to permit additional features to be added in future without requiring a complete redesign of all systems. The following criteria were found throughout varied literature and Ellis [143] summarises ideal performance criteria which he rightly notes are often conflicting and difficult to achieve:

- Low apparent mass/inertia - additional mass can be a new challenge
- High structural stiffness - reality of impacts with VRE
- Zero (or very low) backlash – control and repeatability of movements and measurements
- Absence of mechanical singularities - instabilities are not acceptable
- Accessibility to the operator - users and carers need cost-effective access
- An even "feel" through the workspace - inconsistencies of movement or force disrupt the value of the VRE unless planned
- Low friction – essential for free movement and consistent feel
- Back-driveability – specific to haptics but relevant to free-moving systems
- High force bandwidth - ability to measure or respond to oscillating forces
- High force dynamic range - ability to measure or respond to large and small forces or accelerations
- Compactness - self-contained and usable in most spaces without special services - domestic and some clinical use may depend on this
- Good transportability - should be readily moved and set-up without elaborate calibration

A standardised approach to the design of any system is good engineering practice and for commercial designs it is essential if an affordable and accessible solution is to be achieved. Modular design with interchangeable sub-assemblies, using readily available components, is desirable and suitable components are generally available at the scale of this device. By adopting a scalable design, numerous configurations of the same basic device can be realised for use in different settings for children or adults with acute or chronic needs associated with ABI, TBI, sports rehabilitation, etc, described in section 3.1.

IT is easier to seek approval for a wider variety of applications when hardware is designed with pre-approved and certified equipment and components. Similarly, established manufactured components have known or predictable lifespans and can be selected for their anticipated duty. This would lead to fewer failures in service and if they did fail then replacement would be predictable and achievable. Good design approaches for components in contact with humans is well established and standards exist which can be met using normal design methodology.

The software design and configuration is important to ensure a meaningful VRE is maintained and that suitable measurements can be taken and stored safely. It is also critical to maintaining appropriate safety standards for haptic devices. Separation of controllers for drives, measurement, computer processing of the VRE, and data logging provides for independent building modules which can be tested in isolation. In this way, sub-systems can be tested and approved and unexpected interactions within a larger system minimised and made more traceable.

Complex and engaging VREs are already in common use on gaming and ART devices. A standard PC has sufficient processing power to host such environments as well as store large quantities of data. Typically, the integrated nature of operating systems prevents isolation of individual software modules and uncontrollable delays may be introduced as a result. Even high-performance PCs are not capable of sampling and utilising real-time data in critical control interfaces together with a VRE.

To facilitate potential future medical devices directive (MDD) evaluation, all drive and control functions should be performed by a standalone low-level control system. This provides isolation of critical control functions and traceability of control algorithms. Although data will be exchanged across modules, the actions of the modules should not be contaminated by errors or failures in another module. A high-speed data interface will allow a standard PC to host the visual components of the VRE. A task-specification interface for therapists and the logging of patient biomechanical task-performance data can also be hosted on the PC. The VRE could include any number of scalable age-appropriate games and tasks which the therapist selects.

The primary purpose of initial trials described in section 3.6 was to assess the effectiveness of a new ARMaT device and the activities used by it. A systematic procedure was established for measuring, gathering, storing and retrieving data. The potential large quantity and complexity of the anticipated data, together with the need for real-time and post-processing required a high degree of automation. Initial trials were planned to inform the following sessions and selective data processing and storage was required for maintaining patient records. These considerations led to the following outline data management plan.

Participant records and stored data need to be secure and preferably anonymised and a suitable coding system is required to ensure that data is not confused with other users or sessions. This can all be automatically coded into the file structure of output files based upon initialisation screens for each user.

4.1.4 New ARMaT Device Design Development

This research project has delivered a number of devices in order to develop and meet the performance objectives noted in chapter 1 and the performance specification outlined in section 4.1. They are documented here as the development of the final prototype evolved from the lessons learned in the preceding concept designs, as outlined in the methodology described in section 3.6.

Three distinct devices, all 2-D and desk-based, were developed and used in lab testing. In addition a further three variant devices were developed to progress the design of relevant prototypes. These are not documented here as the three discrete devices below embody their content.

The limitations noted with prototype 1 were surmountable but not in the timeframe of this project. Development of prototype 2 to address these limitations is discussed in section 6.4 and section 7.2.

4.2 Concept A: Early Haptic Design Solution

This was a proof of concept haptic system for laboratory development based on Cartesian arms as shown in Figure 4-8. This device operated with a very basic VRE to assess real-time interaction with users. This concept was intended to establish the feasibility of an affordable modular design using standard stepper motors, simple load measurements and a PC as a common controller and VRE interface. The PC-based controller failed due to real-time interrupts and Windows™ OS limitations which were never resolved and forced a number of design changes.

The stepper motors proved inappropriate for position measurements and were replaced with pancake motors and optical encoders which provided reliable positional data smooth XY motion. Similarly, the spring-based force measurement shown at the front (end-effector) of the device was too flexible and proprietary load cells were used to maintain stiffness and to control response times.

Whilst these modifications to the original design solved a number of issues, the software and hardware instabilities were difficult to overcome and were unlikely to be resolved. The unwanted interaction between biological and engineering control responses could not be isolated without relying on significant filtering and/or signal modification. Such modification was undesirable as it might mask the true behaviour of the participant. Additionally, the required drives, controllers and force transducers were considered to be too expensive and cumbersome for domestic deployment and were unlikely to be reduced significantly.

4.2.1 Preliminary Design

This device was developed from of the original briefing with the clinicians some of which predated the author's involvement. The agreed specification is summarised in Table 4-3 and

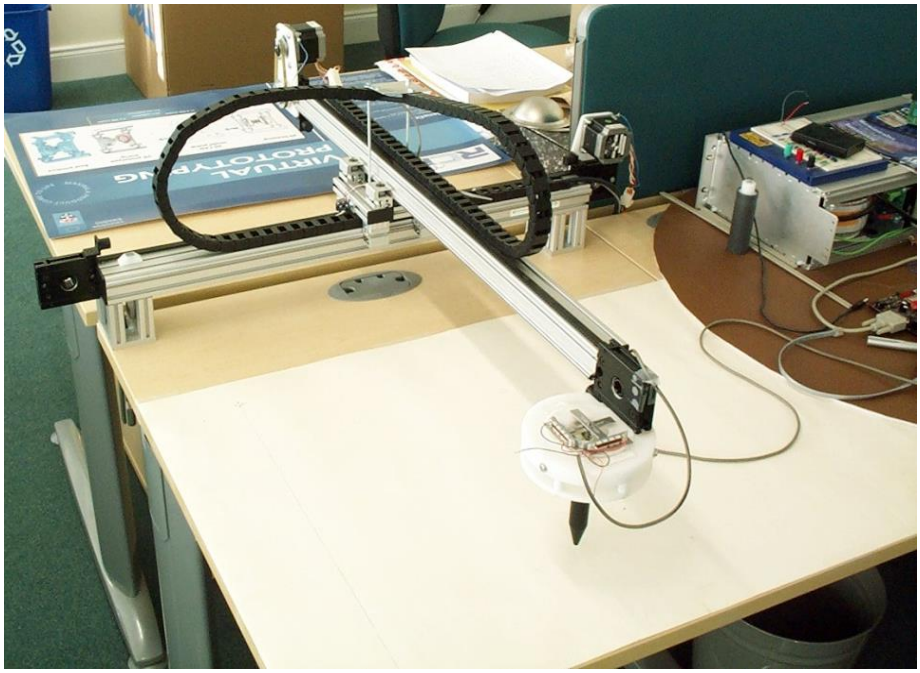


Figure 4-8 Concept A - Cartesian Design

helped to inform the general performance specification in Table 4-1, although this was developed after the start of the original project.

Table 4-3 Design Basis for Concept A

Design Consideration	Value	Units	Remarks
Operating Envelope	600 x 600	mm	Minimum workspace 300 x 300; 2D planar reaching space
Maximum speed	2000	mm/s	Active and passive
Position resolution	1.0	mm	Higher accuracy possible but not necessary for therapy
Normal drive force	5.0 to 25.0	N	Software variable. Safety limits and "break-off" emergency shutdown to be provided
Resolution of drive force	0.1	N	Human perception is normally limited by tactile displacements in the finger tips.
Free running force	0.1	N	Designed to maximise sense of movement in "free-space"
Safety limit for applied force	20-45	N	Disengage at pre-set level; appropriate level to minimise interruptions to therapy sessions
Arm support	-	-	Common fixing point for varied hand and wrist fixings to suit patients' needs
Inertia	Not determined	kg	Minimise in design but can be accommodated by active control system
Stiffness of haptic interface	Minimum 20 N/cm	N/mm	High stiffness desirable – "hard rubber wall" analogy; software adjustable [146].

An admittance control paradigm was adopted due to the inherent physical properties of the device and desired load capacity. The specification shares many common criteria with devices used in similar research as noted in section 2.4.5.

Whilst the VRE and actual movement of the end effector required relatively low resolution of position and force to meet typical therapeutic requirements, the control elements required a ten-fold refinement in resolution; 1.0 mm to 0.1 mm and 0.5 N to 0.05 N respectively. This requirement was identified through early testing when attempting to improve overall stability of the hardware and software based upon the original design using stepper motors and the PC OS. Increasing the sampling rate provided additional data points from which to establish trends in movement or force prediction. These were in turn used to control the drives in response to movements from the user. Whilst partially successful, this requirement dominated the technical specification of the system components and ultimately limited the performance of the concept A device. Continuous sampling rates could not be accurately determined or controlled from the software due to uncontrollable software interrupts in the OS.

4.2.2 Data Records

Raw data to be recorded for subsequent processing and analysis is identified in Table 4-4. It was anticipated that selected data would be used to identify progress through the exercises based on the success of the patient in achieving set tasks rather than measuring actual performance parameters as used for prototype 1.

Table 4-4 Data to be Recorded During an Assessment

Parameters to be recorded	Units	Resolution	Sampling Rate
Position	mm	1.0	2000 Hz; based on maximum anticipated velocity.
Velocity	mm/s	1.0	2000 Hz; to be derived from positional data
Acceleration	mm/s^2	1.0	2000 Hz; to be derived from positional data
Force	N	0.5	2000 Hz; based on required positional accuracy
VRE interface	mm	1	Coincident VRE location with actual device. Depends on screen size and resolution.

In an attempt to solve stability issues the system was redesigned using two capacitive force transducers (X&Y) and a dedicated programmable integrated circuit (PIC) micro-controller with DC drives and optical encoders. This modification provided direct reading of force rather than relying on the spring-balanced resistors coupled to the handle. The spring stiffness was selected to reflect typical input forces (0-25N) and hence these springs were relatively weak given the required displacement at the linear resistor. The associated low damping resulted in a "soft" interface with the user which did not reflect user inputs. The result was unpredictable instability, particularly following rapid or large movements.

Positional measurements were originally implied from stepper motor counts in an attempt to minimise cost and complexity. The discrete nature of the drives (720 steps per revolution) was not thought to be a significant issue but DC pancake motors were used instead as they provided more controllable speed and predictable torque characteristics which might be mapped into the controllers. The optical encoders permitted direct reading (via fixed belts and gears) of actual movement of the end effector and decoupled positional accuracy from drive characteristics.

4.2.3 Design Revisions

The revised working design for the concept A device is shown in Figure 4-9 and used the same simple and robust X-Y plotter design shown in Figure 4-2. The encoders (mounted adjacent to the pancake motors) provided positional data to the PIC which replaced the OS for control of the drives, avoiding software interrupts, etc. Capacitive force transducers were mounted in line with the X and Y axis and these provided direct measurement of the forces exerted by the user on the device. The factory calibrated devices were selected as they required negligible displacement which was thought to be one of the main causes for instability with the previous spring-balanced resistor design. Whilst this arrangement proved to be more stable and predictable it was still unsuitable for use with participants. Occasional

and unpredictable instabilities which manifested themselves as random and sometimes prolonged movements and oscillations could not be isolated and controlled. Although the concept A system proved unsuitable, the design requirements for the controller were appropriate and are recorded below to describe the approaches adopted in subsequent designs.

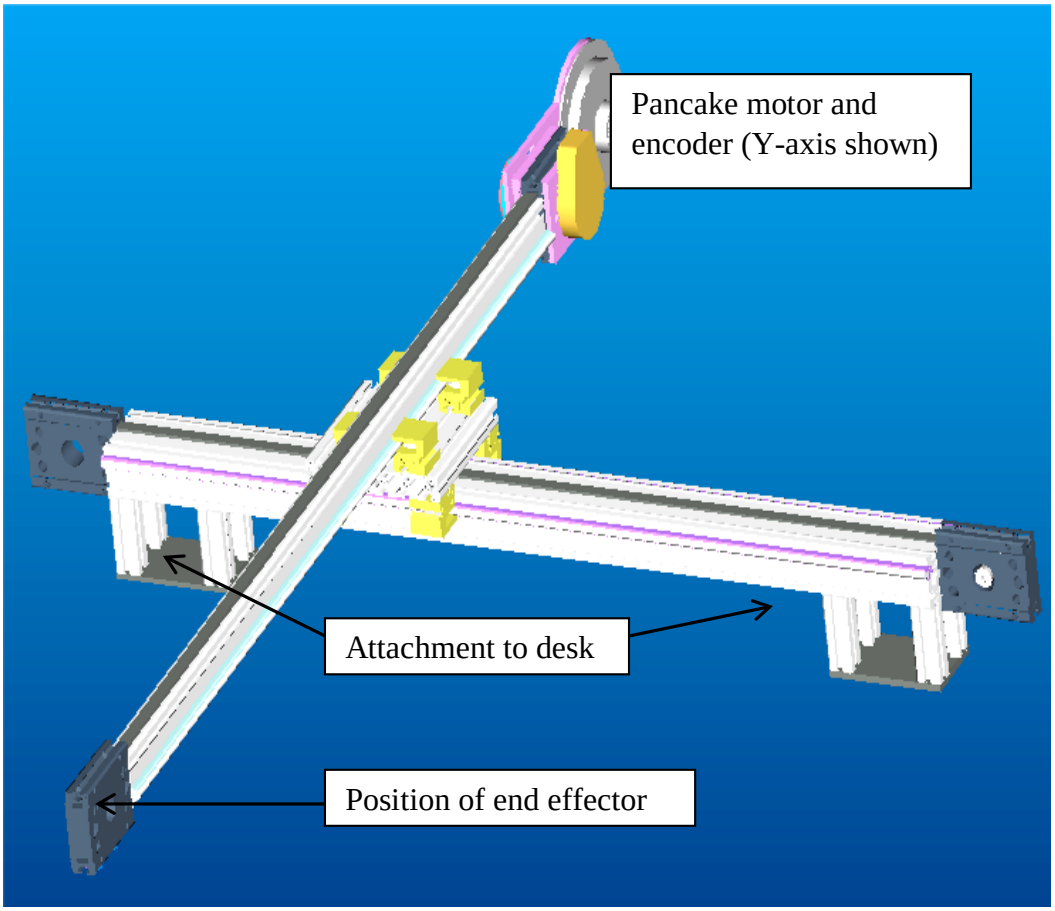


Figure 4-9 Concept A - 2D Cartesian Arms

4.2.4 Control and Monitoring

The controller for the device is summarised in Figure 4-11 and is based upon the de-coupled control provided by the PIC solution. This should have been a feature in the original design of concept A as the use of such device is governed by the MDD as noted in section 4.1.3 earlier. This schematic shows the various components of the system and how they are related to the device drives and safety features. From this diagram, expansion of this functionality to provide 3-D movement is obvious although there are practical issues as noted in earlier.

Figure 4-10 shows the sensor and data schematic and links to the main control functions. The separation of the primary data gathering, control commands and VRE are important to maintain user safety and data security as noted in section 4.1.3. The VRE was intended to be varied to suit the user, their immediate ability and any potential changes, whether such changes were potentially rapid, as may occur in patients with TBI, or predictably slow such as in patients with CP. This was not developed beyond basic movements as it became apparent that this system was unlikely to succeed due to control and stability issues despite the redesign of the drives and controllers.

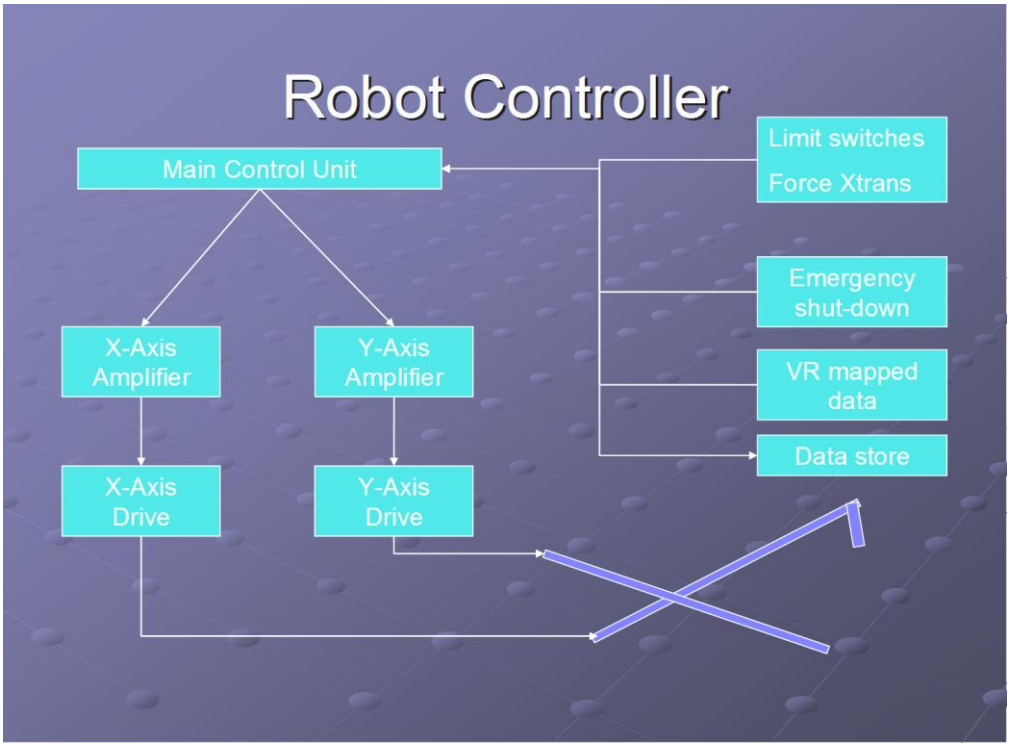


Figure 4-11 Concept A - Control Block Diagram

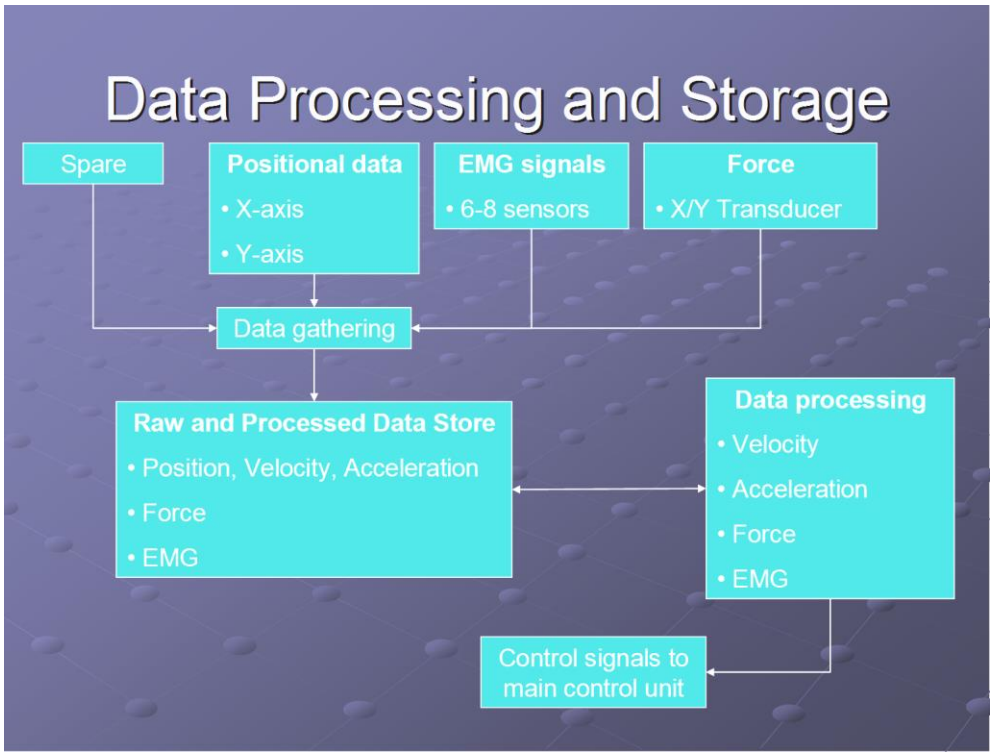


Figure 4-10 Concept A - Data Gathering and Processing Schematic

4.3 Concept B: Non-haptic Design Solution

This device was intended as proof of concept with laboratory testing and limited normal participants drawn from the author's adult colleagues. This device was not intended to test ability, rather to assess the potential of using a very simple measuring devices such as PC mouse. The testing established usability and user comfort as well as operational limitations such as responses to rapid ballistic and periodic movements. This was a non-haptic device based on PC mouse data with simple exercises in a basic VRE to establish validity of using a PC mouse as a real-time measuring system.

The haptic element was removed following the issues noted with concept A and the desire to concentrate on establishing a measure of ability based upon simple movement parameters. The mouse was housed in a bespoke handle to permit easy manipulation and prevent rotational corrections by the users. This was achieved by restraining the handle within four elastic straps on a flat playing surface. The observations of real-time adaptation by users are discussed in section 6.5.

The mouse data proved valuable and reliable except that the Windows OS interacted with the VRE and introduced random data clusters of fixed values instead of a continuous real-time data stream. The simple reaching tasks were valid and appreciated by all users and provided early insights into user interaction and learning of simple tasks. The device was based on a standard low-cost PC, it was compact and easy to use and required only limited additional equipment. Unfortunately, no original images of the finished system survived a flood in the author's office.

The limitations of the concept A device demonstrated the considerable difficulties in developing a stable haptic device. It also highlighted the need to identify suitable measurement for assessing ability and hence rehabilitation progress. Hence, concept B evolved from the primary need to obtain measurements of upper limb movement using simple affordable interfaces. It sought to identify any issues and potential variations between normal and patient participants and to assess the reliability and repeatability of 2-D table top reaching movements in real-time when linked to a simple VRE. The intention was to isolate movement parameters for a variety of participants based upon repeatable reaching movements alone.

Much of the preliminary work on haptics described for concept A earlier was adopted in the development of concept B. Clearly, there was no active force component, although passive forces were present in the form of the inertia of the device, friction at the playing surface and the elastic straps used to hold the sensor and skate in position.

The data in Table 4-1 formed the basis of the design specification for the hardware and was based upon the work developed for concept A. There was no significant change in the basic operational requirements for the concept B device, rather that they be achieved without the need for haptic interaction. Although specific values are indicated in the specification, these were adopted as guidelines and did not limit the design development.

This device was developed following an extensive review of the successes and issues noted for concept A. The selection matrix in Table 4-5 was used to help determine the design and performance requirements of a new ARMaT device against the performance requirements noted in Table 4-1 and subsequent sections. A simple scoring system was proposed by the

author with a mark of five indicating the best arrangement to meet the objectives for an affordable solution. Such a table does not exist for concept A as the Cartesian frame and original sensors, drives and controllers were already in place when the author joined the project.

As noted in section 4.1, design is a somewhat subjective process as not all design elements can be fully assessed without further development of each design solution. Developing the various solutions in Table 4-5 was not considered appropriate given the resources available to the project. The ratings offered in Table 4-5 were based upon the author's judgement from previous industrial product design and development, anticipated relative costs and complexity of manufacture. The measurement systems could be common to each non-haptic device solution so the decisions were largely based upon complexity of design, availability of components and use of common manufacturing processes. Based upon the author's ratings the skate arrangement was favoured for concept B, indicated by the total score obtained from the equally-weighted criteria. Clearly, this approach is open to review and other designs might offer valid solutions to the same problem.

Table 4-5 Design Selection Matrix for Concept B

Criterion	**Figure 4-2 Cartesian Arm (2-D)**	**Figure 4-4 Skate in tension field (2-D)**	**Figure 4-3 Polar Arm (3-D)**	**Figure 4-5 Mechanical Linkages (2-D)**	**Figure 4-6 Heavy Polar Arm (3-D)**	**Figure 4-7 Light Rotating Arm (2-D)**
Capital Cost	3	5	3	3	3	1
Operational Cost	2	5	2	3	3	1
Complexity	3	5	3	3	4	1
Modularity	3	5	2	3	2	1
Adaptability	2	3	3	4	4	3
Ease of use	3	5	4	4	4	4
User safety	3	5	4	2	4	2
Space take	2	5	4	4	2	3
Haptic potential	4	3	4	4	3	5
3-D potential	2	1	3	2	2	5
Total	27	42	32	32	31	27

Note: Scoring: 5 = most favoured, 1=least favoured

It was intended to use a standard PC as the main visual interface and storage medium and so it was logical to use the PC mouse as the primary sensor for position measurement. The PC mouse proved to be sufficiently accurate and scalable to provide relative positional measurements through the Windows OS at insignificant cost; the cost of a mouse being less than £5 at the time of testing.

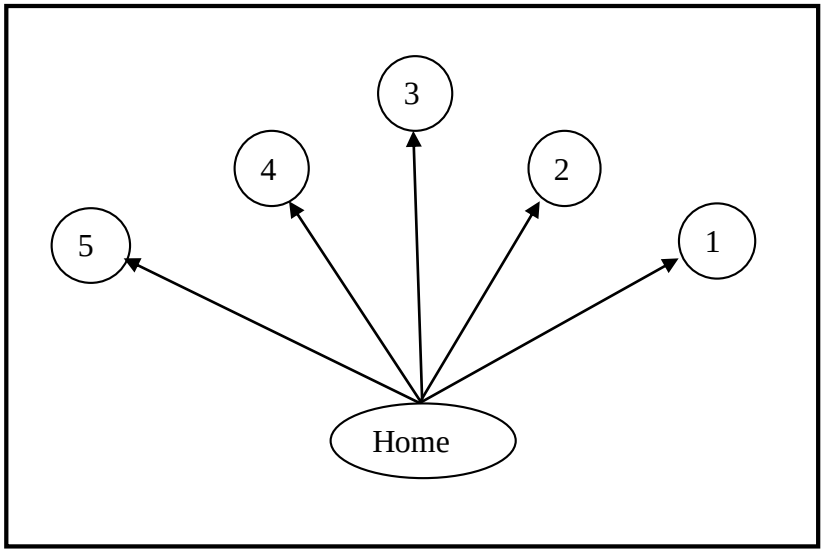


Figure 4-12 Basic Fan-game: Five Targets and Home Base

The VRE was generated within the Windows OS environment. All of the required screen-to-user and mouse-to-screen interactions were available within the PC software as there were no drives required or forced movements. The device became a simple variant of a typical PC gaming environment. This was anticipated to reduce many of the requirements for clinical approval and this was indeed the case; the resulting device was little more than a captive mouse moving on a special table top.

4.3.1 VRE Design

The most appropriate VRE for measurement, and potentially for future therapy, was decided to be a simple game-type environment. This had been used in a variety of ART systems as noted in section 2.4.5 and was demonstrably effective. The initial game design required a simple visual interface which could challenge the user without distracting them. A fan-game, see Figure 4-12, was developed which allowed a range of movements from a fixed home base across the working surface. This has similarities to other research in this area, see section 2.7, and was considered the most appropriate for a simple environment.

The user was prompted by basic sounds and a count-down to the start of the game. Game play started at the home position and the targets appeared on the screen to direct the user towards it. The sequence of targets was varied to limit opportunities for users to anticipate the position of the next target

4.3.2 Hardware Considerations

To understand how participants might interact with the proposed skate and VRE, a number of ad-hoc observations of patient participants (not part of the subsequent clinical trials with prototype 1) were carried out with the assistance of the therapist at NGH. The author conducted similar observations with a group normal teenage participants at a local youth centre. These observations were opportunistic and provided valuable insights into how new participants might approach and use the system, and in particular the skate containing the mouse.

4.3.3 Skate Design

In an attempt to accommodate a wide variety of users with variable grip responses, an elaborate design was proposed and partially assessed. The preliminary design is shown in Figure 4-13 and included an adjustable height horizontal wrist support together with an adjustable vertical grip handle which allowed variable wrist rotations to be accommodated to avoid over-turning during less-controlled movements. It was found that such an elaborate design was not needed for the patient participants under examination and more simple handle designs were used which provided adequate stability and support.

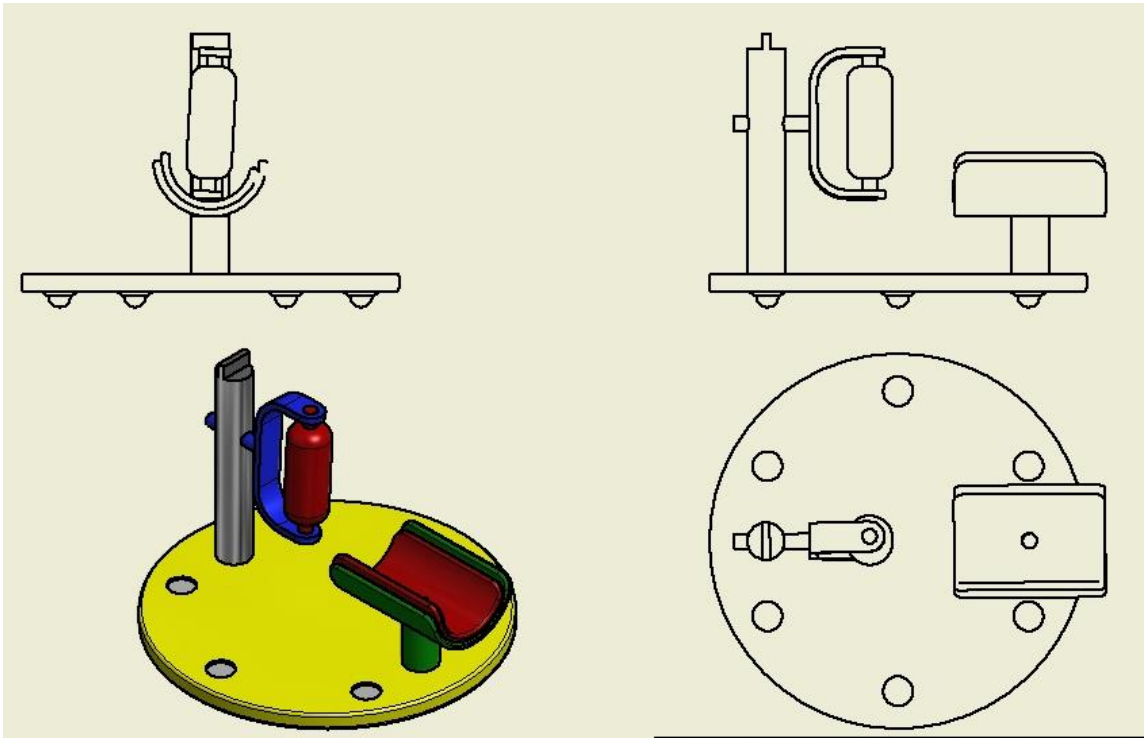


Figure 4-13 Skate Platform with Additional Support and Features.

There were two basic skate designs (circular and rectangular) produced in order to assess the required skate footprint and the stability to the mouse that it provided. Figure 4-15 shows a basic rectangular skate platform with a fixed vertical handle supported on four rotating ball feet. The long axis was intended to align with the forearm and to provide support to the user. As shown the platform was too small for both comfort and stability and two larger variants were assessed together with symmetrical designs. A circular design with an outside diameter

of 150 mm was favoured for the all-round stability and support that it provided. It also offered no indication of direction of travel that might confuse or direct a user to follow a certain path.

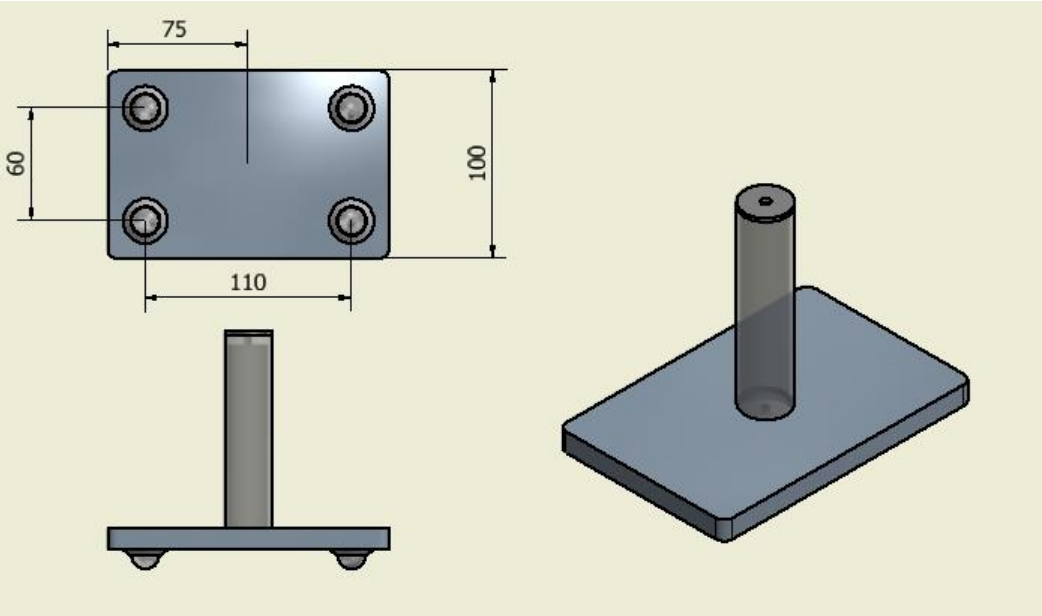


Figure 4-14 Rectangular Skate Platform with Vertical Handle

The vertical handle in Figure 4-15 required a neutral hand position that was not comfortable for most patient participants and even for some normal participants. Three distinct handle designs were proposed to assess patient comfort and preference for pronated or neutral hand orientations. These were a simple ball (diameter 30 mm) on a stick (100 mm high) that might be used with a neutral or pronated hand position, a similar ball on a short stick (25 mm high) suited only to pronated use, and a simple horizontal loop handle suited to pronated use. This

Figure 4-15 Loop Handle Design

loop handle arrangement is shown in Figure 4-14 which is taken from Figure 4-16 which shows it being used by a healthy participant during early assessment of prototype 1.

Patient participants preferred pronated hand positions to neutral orientations and this probably reflected familiarity with using a PC mouse as well as being a natural resting position. Normal participants appeared to able to use any type of handle or skate designs effectively and could move the skate rapidly if desired. In contrast, patient participants moved the skate relatively slowly and deliberately often adding trunk movements to augment limited arm movements. As supinated hand orientations are not used in most reaching tasks these were not assessed.

Both groups tended to overturn some of the skate designs when encouraged to move quickly and particularly when using the vertical handle or ball and post designs. It is possible that a larger half-ball design may have been as effective as the loop handle but this was not attempted.

Patient participants showed little interest in the handle with a ball on a short vertical post. This appeared to be due to an inability to grip the ball reliably, the hand falling off the ball when the skate was moved. Patient participants with little or no grip response preferred the horizontal loop handle to a vertical stick handle although some patient participants could hold the vertical stick handle. Where there was little or no volitional grip, the OT placed the paretic hand over the loop and the participant's fingers curled around the handle naturally. This seemed to locate the handle in the palm securely and allowed good control of the skate. It also seemed to be a more comfortable position and allowed some participants to rest some of the weight of their arm on the skate.

4.3.4 Seating and Support

Normal participants appeared at ease attempting the fan-game using the laptop screen alone whilst seated in any chair at an office type open flat desk. For some patient participants, a more supportive chair with adjustments to height, seat tilt and back support were necessary, as determined by the OT. Similarly, patient participants appeared to benefit from using a separate screen mounted approximately 150mm above the playing surface. It was concluded that this may have been as a result of less flexibility or control of the trunk during reaching movements which may have affect the participants view of the screen. This arrangement had the added benefit that the OT could set up each fan-game without it becoming a distraction for the patient participants. Normal participants did not appear distracted by this process.

4.3.5 Fan-game Usability

The fan-game was almost trivial for most normal participants when using their dominant hand but became more of a challenge when using their non-dominant hand. This pattern of behaviour was repeated for the patient participants although they appeared to require greater effort and care with either hand. Although the effect of a heavier skate assembly was not assessed, it was evident that both participant groups were managing to move the skate with ease.

There was no evidence that any participant could not understand the task or identify the targets, cursor, home base and audible cues within the audio-visual interface

The possibility of requiring the user to click a mouse button or press another button was assessed during preliminary observations of patient participants at the NGH prior to the start of clinical trials. This additional action was abandoned as few if any of the patient participants observed could operate a mouse button easily with their non-dominant hand. Also, it was noted that use of their dominant hand might introduce unknown delays or coordination issues that were not relevant to the measurement task. This issue was noted in section 2.7.

There was another issue raised by the dual requirement to press a button when moving the upper limb. If sensorimotor re-learning capacity was limited, adding a quite different fine-motor finger/wrist skill to the gross and fine skills of the upper limb segments may limit the progress of learning by overwhelming the available capacity. As rehabilitation progresses, this may well be a suitable additional challenge to assess extended coordination within the same limb or potentially the opposite limb.

Attempts to minimise friction between the surface and the skate resulted in a variety of modifications including using captive ball bearings (see Figure 4-15), low friction materials on the skate and playing surface and combinations of these. The least obtrusive, most reliable and most tolerant designs were found to be based on low friction table surfaces and matching feet on the skate. The low friction arrangement was retained for prototype 1 and is shown in Figure 4-16.

4.3.6 Data Considerations

Positional XY data and times were measured with concept B being derived from the mouse coded data as interpreted from the bespoke software. This proved to be the most unpredictable element of the whole system. Attempts to operate within the Windows™ OS using proprietary drivers caused a number of issues with data clustering. It was noted that groups of data points were stored as identical values for position and time despite movement having taken place which should have resulted in changes in the data stream. The effect appeared to be random and unrelated to any other operational activity. This issue appeared to be a result of the OS and despite attempts to isolate and remove this problem, it was not possible to do so.

The fan-game VRE was supported on the OS successfully and was hard-coded. This limited development beyond the fan-game arrangements established in Figure 4-12 which restricted the gameplay to the single fan-game geometry. This was not a significant limitation as the fan-game had been determined as a suitable assessment. However, greater flexibility to develop more geometries was seen to be desirable in the clinical prototype to allow variation in length and angle of anticipated paths if the planned design proved inadequate.

Data files were stored after gameplay and accessed using MS Excel. The system worked effectively using the standard PC monitor and speakers and as such any medium specification computer system would have sufficed.

Basic positional accuracy and time checks were carried out and are recorded in appendix 4A for a variety of movements based on the anticipated fan-game geometry. These were deemed satisfactory, being within the requirements noted in Table 4-1.

4.3.7 Anticipated Costs

The anticipated costs are summarised in Table 4-6 and these were used as a baseline from which to assess the viability of such a system given that it would provide valuable ARMaT functionality. The total is within the target cost of £1000 determined as being affordable in section 3.1.2.

Concept B demonstrated that usable positional and temporal data could be obtained using a simple PC mouse, standard PC system, simple hardware and VRE. Preliminary results from normal participants drawn from the author's colleagues showed that the hardware and software with the fan-game provided the potential to differentiate between users, practice intensity and acquired and native skills. The need for a more acceptable and appropriate prototype for use in clinical trials formed the basis for developing prototype 1 which is described below.

Table 4-6 Concept B - Anticipated Production Costs (1000 units)

Element	**Cost**	**Remarks**
PC or Laptop	£300	Basic specification, no additional software
Software	£200	Windows OS plus development and maintenance costs
Playing surface	£50	Basic fabrication and finishing
PC Mouse	£5	Often part of PC package
Skate	£65	To house mouse and provide basic handle
Miscellaneous	£50	Fixings and packaging
TOTAL COST	£670	Complete system

4.4 Prototype 1: Normal and Patient Trials

This device was developed for extended laboratory testing and was subsequently used for clinical testing with normal and patient participants. This device built upon the early successes with the PC mouse used in concept B as it had been proven to be effective as a basic measuring tool.

The PC mouse was housed in a bespoke handle held in a low tension spring field on a low friction surface. This was to permit easy manipulation by all users and to prevent rotations of the mouse, as was noted with concept B. A number of other interfacing modifications were introduced together with improved data capture and transfer.

This device was tested extensively in the laboratory and with normal and patient participants as part of the clinical trials described in section 5.1. However, data transfer rates and interrupts with the PC VRE indicated that a further improved design that did not rely on the OS and mouse was required. Similarly, positional accuracy was in danger of being compromised if further sensors were added or higher sampling rates required so that velocities could be derived. As accelerometers were also proposed to provide additional kinematic parameters, a new design of interface was required and further tests were halted after significant data sets were gathered.

Prototype 1 was the only device to be used with patient participants. It permitted the assessment of potential movement parameters, derived from mouse positional data, for determining performance in simple two-dimensional table tasks. The prototype was used with a patient group who were assessed concurrently using the Melbourne unilateral upper limb (MUUL) assessment and the Tyneside pegboard test (TPT) inspired by the nine hole peg test (NHPT) on a participant group of children as part of another study. This is reported fully in section 5.1.

The prototype 1 device was developed from concept B, and addressed most of the limitations noted in section 4.3 and built upon the observations of various participants using the hardware and software. The major changes from concept B were in forming a larger skate (diameter 175 mm to accommodate the mouse) with a detachable hooped handle on top, see Figure 4-16. The top (wooden disc below the red handle) of the skate was free to rotate whilst the base, which housed the mouse, was retained in a light spring field. This prevented the user from affecting the orientation of the mouse (needed to maintain correct XY positional integrity) during game play.

The basic specification for prototype 1 was similar to that for concept B as many of the features had proved to be appropriate and valuable and closely matched the specification described in Table 4-1.

The arrangement of the final VRE developed from a desire for an assessment environment that would be useful and attractive to children. The assessment would appear as a fan-game with simple rules, achievable but non-trivial objectives, an interesting but not overly complex environment, and facilities to introduce new challenges without learning new rules or environments. A number of versions of the fan-game were developed and tested by the author to ensure that stable and predictable movement data could be obtained within the performance criteria established in Table 4-1.

The issues noted with the early versions of the fan-game running on a standalone laptop were largely resolved using the skate and handle shown in Figure 4-16 and the simple arrangement of five targets and home base shown in Figure 4-12. The preferred loop handle was made from wood and sealed with protective and brightly coloured child-safe paint and mounted on a different coloured skate that housed the mouse. The handle was attached to the skate using hook and loop tape and could be removed quickly if the participant needed to move away from the table. Further handle designs (described in section 4.2.2) were provided in case a participant needed a different style, but these were never used.

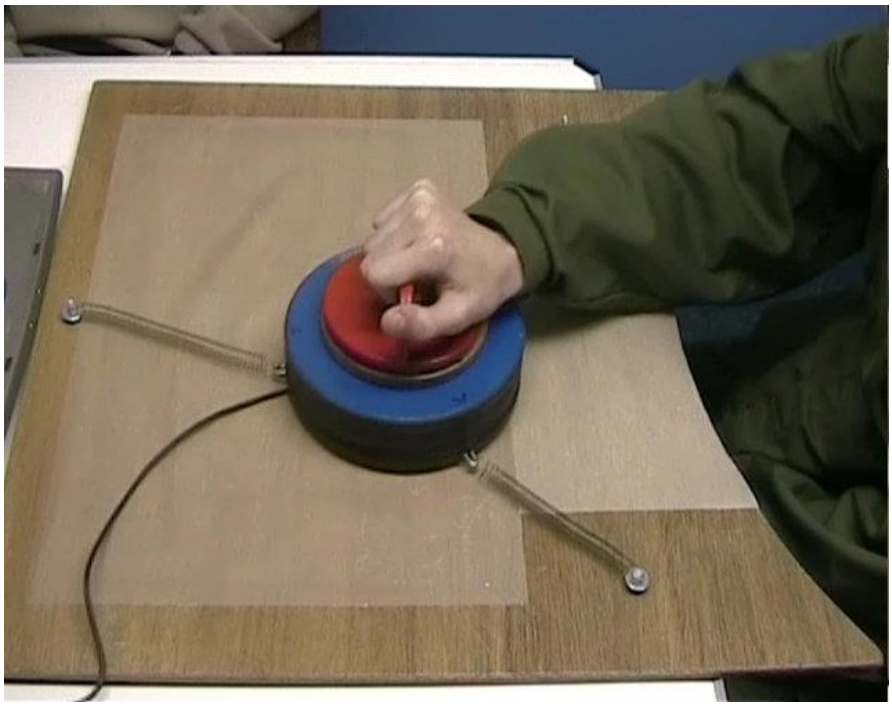


Figure 4-16 Loop Handle and Skate (containing mouse) in a Spring Field

The edge of the skate was covered in dark leather to provide a strong contrast to the working surface and safe soft edge to the skate. The playing surface was made from sheets of PTFE impregnated fabric which were fixed to a flat and coated particle board base. The "feel" of the assembly was considered by users to be warm and unobtrusive. Use of natural materials, where possible, contributed to this.

The hardware was bespoke in arrangement but formed from standard components available from a variety of suppliers. A relatively small number of specific components such as brackets and supports were manufactured to join the otherwise standard elements together to form a reasonably compact and manageable unit. It was notable that the whole system required a rigid fixing to a rigid table in order that that the system remained stable and did not move with the user. This made the working parts less portable than hoped although further development could have resulted in a more compact and self-supporting system.

4.4.1 Game Play

The objective of the fan-game was to move a cursor to hit targets from a common home base Five targets were arranged at fixed distances and angles from the home base with approximately 1:1 scaling between the mouse movement on the playing surface and cursor movement on the screen. When a target was hit an explosion sound was played and the target disappeared. The trigger point for a hit was set as 50 percentage overlap of the cursor on the target as illustrated in Figure 4-17. This percentage overlap was determined as the optimum following a number of trials with all participants. Requiring more than 50 percent provided too great a challenge to some patient participants and less than 50 percent overlap allowed some participants to use largely ballistic motions rather than controlling the skate from point to point.

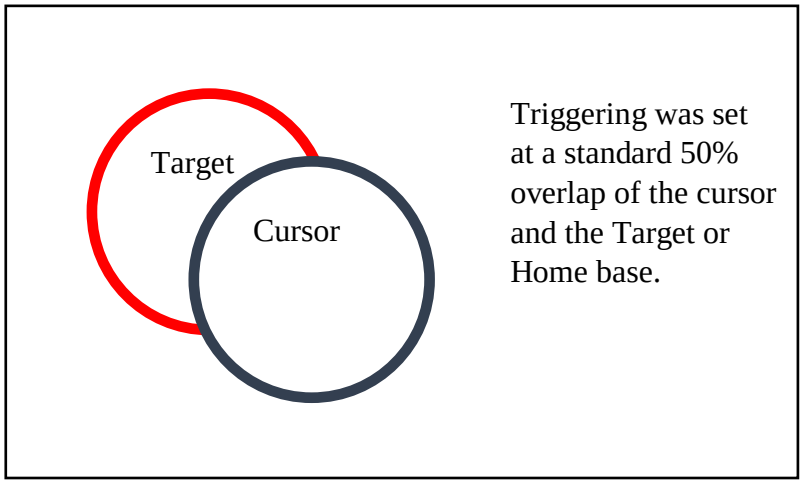


Figure 4-17 Trigger Point for Target Acquistion or return to Home Base

After each target was hit the participant moved the mouse back to the home base. When the home was reached (defined as overlapping of the cursor with the home base; similar to the target) the next target appeared and the game continued until all five targets were removed. Having completed one fan-game the next pattern of targets, as shown in Table 4-7, was presented and so on until all five games were complete.

Table 4-7 Target Presentation Order in each Game (see Figure 4-12)

Game	First	Second	Third	Fourth	Fifth
1	1	2	3	4	5
2	2	4	1	5	3
3	5	1	4	3	2
4	3	5	2	1	4
5	4	3	5	2	1

Planned target trajectories are shown in Table 4-8 together with their angles and trajectory lengths. These were planned nominal values but were found to have varied during software implementation as noted in section 5.1 where calibrated values are presented.

Table 4-8 Target Trajectories Relative to Home Base (see Figure 4-12)					
Target Details	**1**	**2**	**3**	**4**	**5**
Length of Ideal Trajectory (mm)	180	120	180	120	180
Angle of IT from Horizontal (degrees)	30	60	90	120	150

Instructions to all participants were to be standardized and clear instructions provided for the game set up and operation.

4.4.2 Measurements

All distances noted in the parameters in described in chapter 3 were derived from mouse positional (XY) data. These are described as pixels in the raw data due to coding although their actual values are related to cursor movements on the screen. For example, a movement of X = 10 and Y =10 from position A to position B describes a path length of 14.14 pixels along a path at 45 degrees to the horizontal. The approximate 1:1 scaling between mouse movement on the playing surface and screen cursor movement indicates that a path length of 100 pixels equates to 40 mm +/- 0.5 mm of mouse movement. Similarly, time measurements were recorded in the software as screen units (su) due to the coding and these required scaling by 0.016. One second is represented by 62.5 su +/- 1 su (0.016 seconds).

4.4.3 Human Interface

The original PC mouse was chosen as a standard ball and socket unit that used contact encoders to provide accurate X and Y movement data streams through the mouse control to the PS2 port on the PC. A high-speed optical device using USB connectivity was also considered and some limited trials were attempted after prototype 1 was implemented. It was anticipated that this would minimise or remove the data clustering issues discussed later but, this proved not to be the issue.

The PS2 mouse was left intact and mounted within the skate, contained within a cavity formed within the skate body and ensuring the correct orientation of the mouse with the spring filed. Data from the mouse was passed to the PC within the Windows™ environment.

4.4.4 Eliminating Unplanned Rotation

The original concept for the fan-game included the potential to introduce virtual challenges, the most favoured being a form or rotational disturbance, added without the knowledge of the participant. Effectively, the software displaced the cursor from the path that the participant chose by a constant angle. For example, in order to follow a trajectory at 30 degrees (to the horizontal) on the screen, the participant needed to push the mouse at an angle of 60 degrees on the table. Many participants compensated for this by rotating the mouse the required additional 30 degrees of correction and then executed a 30 degree path. This unexpected behaviour caused a major review of the experimental approach. It is interesting that the participants who did this actually managed to adapt their behaviour in real time, often hitting the target as well as those without any rotational correction. It is notable that whilst the proposed challenge was to be a fixed rotation angle, the participants were introducing, and

compensating for, highly variable rotational and lateral movements caused by the uncontrolled rotation of the mouse. The rotational disturbance was available but was not introduced to the clinical trials as the measurands for simple movements were required before additional complications were considered.

4.4.5 Anticipated Costs

The anticipated costs are summarised in Table 4-9 which contains similar components to that for concept B.

Table 4-9 Prototype 1 - Anticipated Production Costs (1000 units)

Element	Cost	Remarks
PC or Laptop	£300	Basic specification, no additional software
Software	£200	Windows OS plus development and maintenance costs
Playing surface	£75	Basic fabrication and finishing
PC mouse	£5	Often part of PC package
Skate	£75	
Miscellaneous	£60	Fixings and packaging
TOTAL COST	£715	Complete system

4.4.6 Technical Limitations

There were a number of technical issues that could not be resolved whilst testing prototype 1. First and foremost were problems with data transfer from the mouse to the PC. Although the game-play was reasonably smooth and suitable for the fan-game tasks, the data stored contained a number of unexplained elements in the X and Y position data as previously noted for concept B. Whilst less frequent than with concept B they were still present and unpredictable. These "stationary data clusters" appeared to replicate the last movement values recorded and could add between three and seven lines of identical data. They were considered annoying anomalies as they did not appear to affect any data measurements as video footage and the author's testing showed that the mouse had not been stationary at any point. Less common but still of concern were missing data values resulting in a stored value of zero when the data either side contradicted this. For affected games this was manually adjusted, removing data clusters and then re-formatting the data. The results showed continuity of path and only rarely were significant discrepancies noted.

As a result of significant testing and examination of the data, the author concluded that removal of data clusters and zero values was acceptable without notable changes to the test results. In consultation with the software engineer, it was concluded that the mouse controller system was working satisfactorily but the PC OS and/or mouse interface were introducing unpredictable delays that did not reflect actual motion. Despite continued efforts these errors could not be isolated and resolved.

4.5 Chapter Summary

In this chapter a performance specification was offered based upon the literature review and engineering judgement. This was developed to support the design of three discrete and one proposed device. The limitations of the original haptic ART device were examined and the justification for developing a simple ARMaT device offered. The design development of a working ARMaT concept and prototype were explained and their merits and limitations identified.

Working designs for two concept devices and the prototype were proposed and justified based upon developments and early testing. Clear progression from each design is documented based upon lessons learned when working with normal and patient participants.

Anticipated cost were provided for the concepts and prototype based upon potential limited initial batch production which meet the proposed performance specification.

5 Results

The results reported here were obtained with prototype 1 using the simple reaching movements contained in the fan-game, as noted in section 4.4. Patient and normal participants were tested in separate groups using the same version of the software and similar hardware. The clinical results were obtained from a patient group of children and a similar group of normal participants. Participant details are reported in section 5.2.

The diagram in Figure 5-1 shows the participants involved, their basic medical condition and the main assessments employed. Also indicated is the nature of the results obtained from the assessment. Participants were divided into four sub-groups: patient dominant and non-dominant, and normal dominant and non-dominant.

The methods used to analyse the movement data from the fan-game and to compare parameters and clinical scales were chosen to be predictable and reproducible. Standard tests were used to assess the suitability of all data for statistical assessment. Data was screened for outliers and anomalous values. The number of participants indicated in Figure 5-1 results from the removal of two participant outliers (one normal, one patient) to ensure normality of the clinical data and hence permit parametric correlations to be conducted.

The median of each movement parameter was used as the representative value for each participant in each sub-group. Parametric correlations based on the median values were used as the most robust method for assessing such experimental data. Non-parametric assessments could have been used but there are limitations in using the non-parametric Spearman test with what might be Gaussian populations. With small samples ($N<12$) the ‘p’ value will be higher than with a ‘t-test’ and it may not be possible to obtain ‘p’ values less than 0.05, irrespective of the differences in results.

Potential relationships between clinical scales and parameters were established based upon both visual and statistical comparisons of datasets. Pre-selection of suitable metric parameters was achieved by two preliminary methods. The first employed an initial regression analysis (IRA) based on the Tyneside Peg Test (TPT) scores to identify dominant parameters in each sub-group. The second used Principal Component Analysis (PCA), a factor reduction technique, to identify parameters in component groups. This process was not intended to analyse the results specifically. Rather is was used to identify a reduced set of common parameters that might be used to form a new metric. The basic process is illustrated in Figure 5-2

The selected parameters were regressed and the regression coefficients used to provide the sign, and potentially magnitude, of initial weighting factors used to form a new metric from linear combination of parameters. The new metric was optimised for correlations with the TPT data, being the common clinical scale within each sub-group. Predicted clinical scores were assessed for fit with the original clinical data and correlations confirmed. The basic process is illustrated in Figure 5-3.

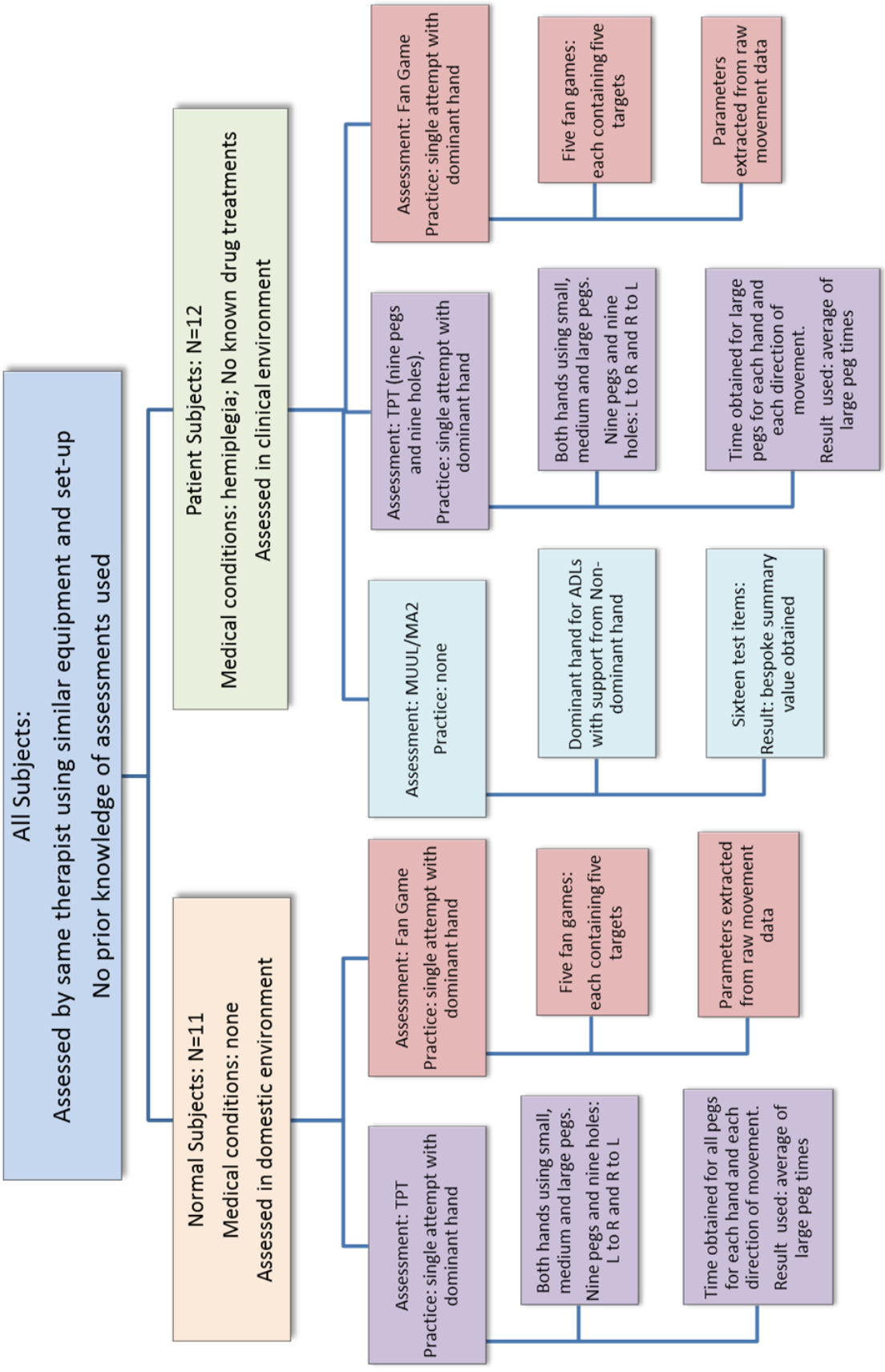


Figure 5-1 Participant Assessment Summary

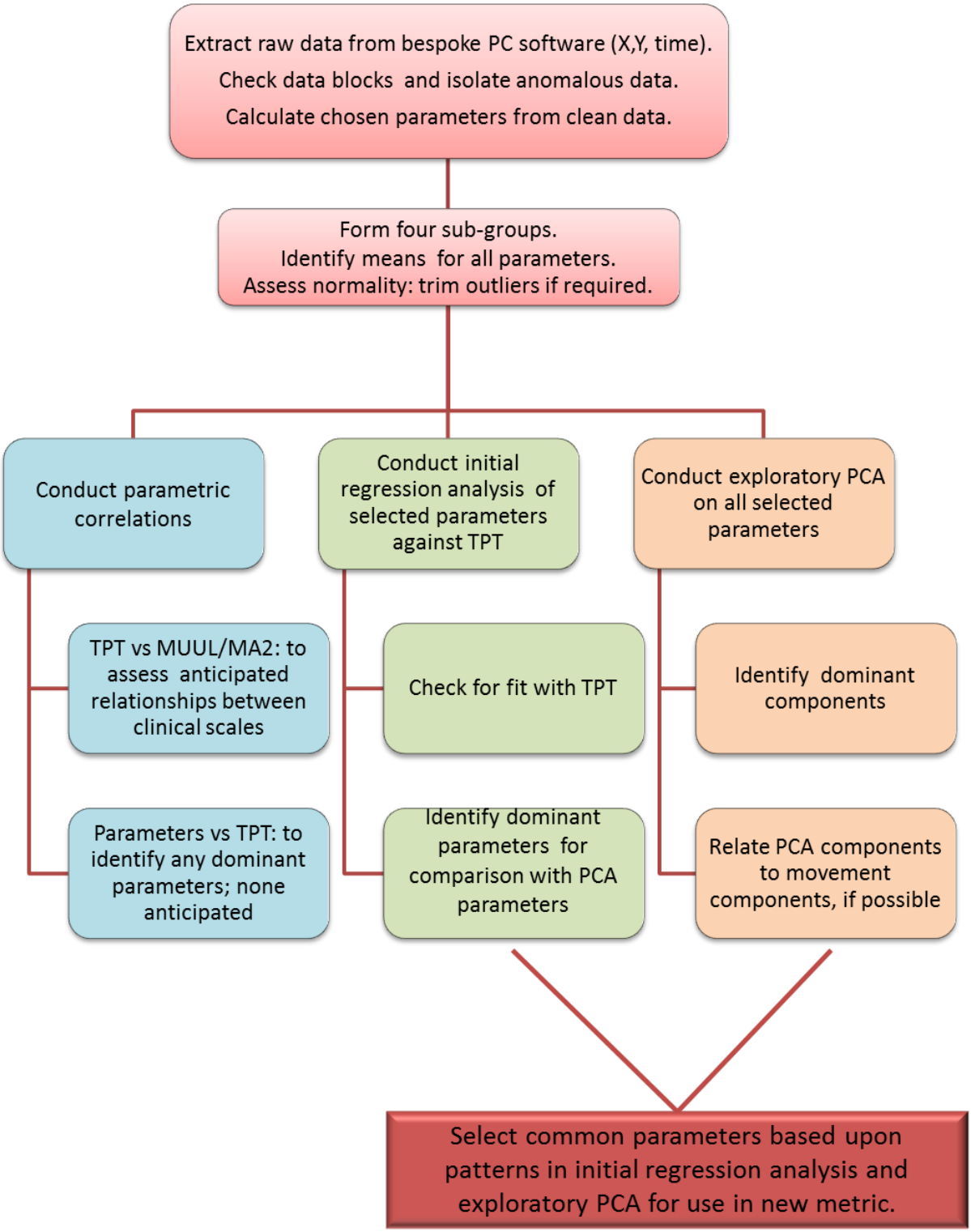


Figure 5-2 Process of Parameter Selection

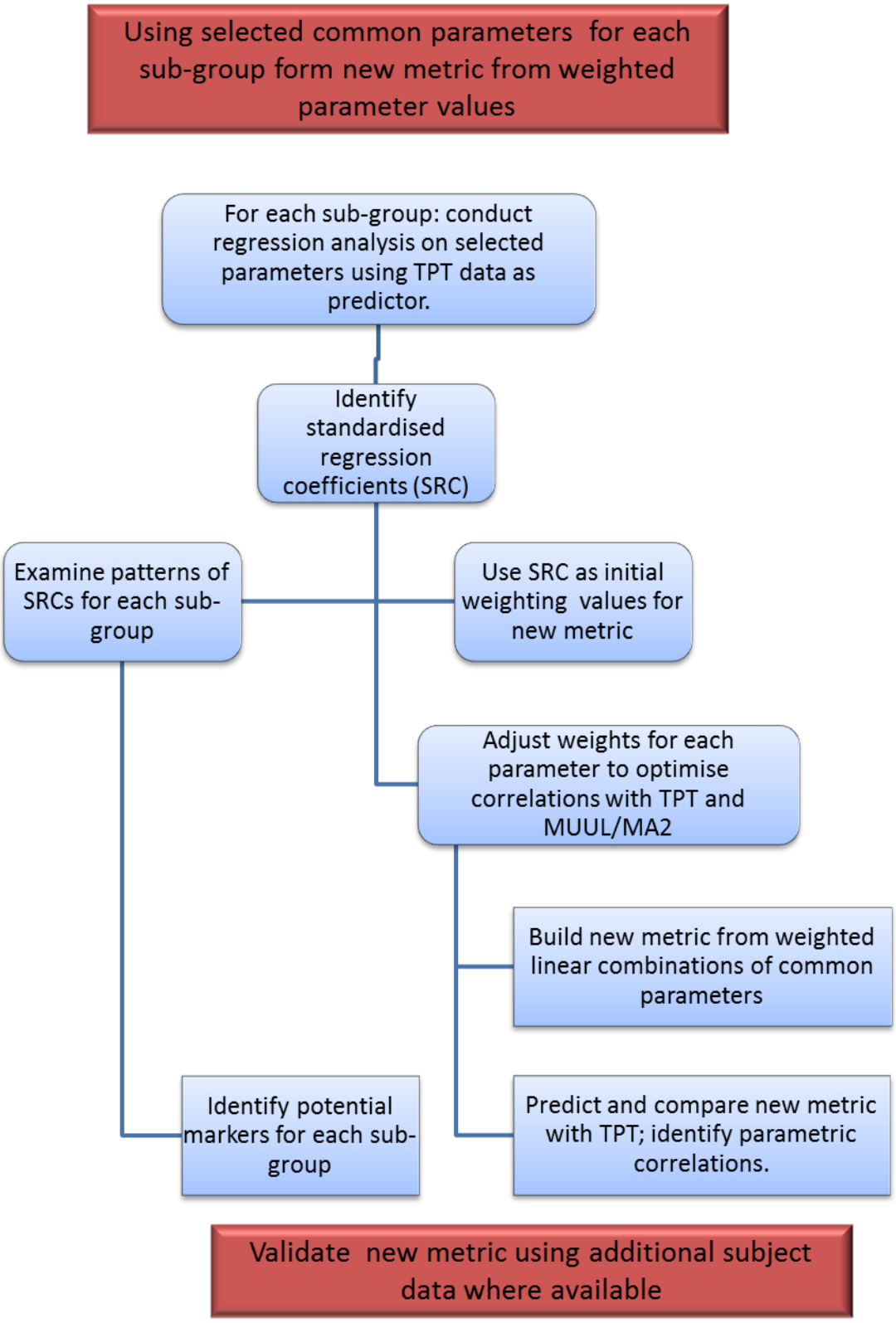


Figure 5-3 Process for Identifyng a New Metric

5.1 Experimental Procedures

This section considers the selection and testing of human participants and the nature of the two clinical tests that were used in parallel with prototype 1.

The value of any data is largely determined by the reliability of measurements and the quantity of data assessed across a representative sample of a given population. Reliability issues were addressed by using simple, predictable and repeatable measurements taken under similar conditions for each group of participants, wherever possible. The quantity of participants was difficult to confirm during planning but to be a meaningful sample there would be more than ten (see below) age-related participants with any given condition. This would permit greater confidence in resulting statistics for the population. It is notable that only a limited number of the papers reviewed in chapter 2 reported data from more than ten participants, even in more diverse participant groups.

To mitigate any potential limitation in participant numbers, repeated testing of any participant was planned. This allowed for assessment of within-participant repeatability and would also permit trends of immediate learning to stabilise. Prolonged repetitive testing has been noted to adversely affect results and reliability [9]. Hence, the development of any testing process needed to ensure that the participant was not unduly stressed, distracted or tired during any session. As the ARMaT device was designed to facilitate rapid assessment, no session should last longer than fifteen minutes and opportunities for resting were to be available at any time.

In order to make useful comparisons between patient and normal participants, two basic criteria needed to be met. Firstly, patient participants needed to be assessed with established tools so that any new measurand could be compared with a known relevant standard and correlations established. Secondly, similar normal participants needed to be tested under similar conditions using the same equipment and test method. The normal participants would establish floor and ceiling effects, if any, and assess the challenge of the fan-game to ensure that they were not trivial for all participants.

Patient participants were sourced from an ongoing trial which also used two relevant established assessments and they formed the basis of the clinical datasets. Although the number, age, sex and clinical condition of patient participants was largely limited by opportunity, sufficient participants were obtained to establish useful data sets.

The availability of normal participants was not considered a particular issue although the selection of age-relevant participants was a little problematic. Informed consent from adults and parents was predictable as the tasks and equipment involved were essentially no more onerous or dangerous than using a normal desktop PC for a short while.

Future planned trials for prototype 2 would include requests from the clinical team as noted below which were not all possible with prototype 1:

- Participants to be of similar ages
- Equal number of male and female participants
- Equal number of left and right-handed participants
- Similar clinical conditions
- Access to the raw data from clinical assessments used

The number of test participants can affect the reliability of any assessment and particularly when using standard statistical tests to assess the validity of any hypothesis. A basic recommendation from is that at least ten participants are assessed to ensure that the validity of the statistical methods is not compromised. The *a priori* sample size estimate was made using the "Correlation: bivariate normal model" in the "G*power" (Heinrich-Heine-Universität Düsseldorf) calculator version 3.1.9.2. This indicated that for a power of 0.8, error probability of 0.05 and correlation for H1 of 0.75 that ten participants would be adequate. Increasing the required power to 0.9 indicated a requirement for twelve participants. Further post-hoc power tests using the same software (correlation: bivariate normal model; two-tail test) were conducted on the new metric based on the correlations with the new metric and these are recorded in section 5.5.5.

5.1.1 Test Conditions for Participants

Due to the nature of the two clinical assessments made, the patient participants were invited to Newcastle general hospital (NGH) where a specialist room was equipped with not only the required test equipment but also multiple cameras to record activities. This allowed post-session assessment for the Melbourne unilateral upper limb (MUUL) assessment and also independent review of the sessions. The video also allowed for subsequent conversion of the MUUL data to Melbourne assessment 2 (MA2) data and to review any issues with the early TPT results. The prototype 1 device was used in the same venue following the other two assessments but required only a table for the baseboard and PC screen. All positional data was captured within the PC and was transferred after the session. Ethical approval for patient participant testing was obtained as part of the ongoing trial and is described in chapter 4.

The results reported here were obtained with prototype 1 where patient and normal participants were tested in separate groups using the same version of the software. The clinical results were obtained from a patient group of children as part of another study who were assessed concurrently using the MUUL and its successor the MA2. They were also assessed using the TPT, a pegboard test inspired by the Nine Hole Peg Test (NHPT) [31]. Correlations between the TPT and the MUUL/MA2 scores are reported in section 5.3.2.

The patient participants were all part of a double blind drug trial as part of a larger research project within the NGH and the author is grateful for the opportunity to be involved with this patient group. The baseline data used in this thesis was taken prior to any medical intervention. Some of the participants were given botulinum toxin to test whether they would learn coordinated tasks more quickly and retain that skill. This is similar to the work by Tegenthoff *et al.* [182] where they noted a marked improvement in "*training-induced motor cortex plasticity*" following the administering of amphetamine to normal human participants. Only limited data for three participants was obtained with the prototype in the three and six month follow-up tests after the baseline data was obtained as noted in chapter 5.

A group of normal participants was used as a control and they were also assessed using the TPT by the same therapist in a domestic environment. The arrangement of PC, skate, handle and baseboard was identical to that for the patient participants.

5.1.2 Assessments Employed

The two clinical assessments are described briefly here although analysis of their data is not considered within this thesis other than to compare them with that obtained from prototype 1. The testing arrangements and planned measurands for prototype 1 are described in chapter 3.

All testing on patient participants was carried out in the same room by the same therapist over a period of time determined by the clinical trial. Not all clinical participants were also tested with prototype 1 and only limited re-testing was possible. Only patient participants tested on both the clinical scales and prototype 1 are reported here.

The two assessments were established by the clinician in charge and specialist equipment was used as described in the following sections. Each assessment was quite different in nature and application, and patients were generally motivated to do well in both by the therapist despite obvious physical and cognitive difficulties at times. Patient participants were assessed using the original MUUL criteria which were current at the time of testing. As all of the tests were recorded on video, they were also reassessed under the revised and refined criteria for MA2. Both sets of data are presented in chapter 5.

Ethical consent was obtained from the joint ethics committee (comprising north Tyneside health authority, Newcastle university and Northumbria university) for the CP group. Informed consent was obtained for adult normal participants and parental consent was obtained normal children, all of whom volunteered.

5.1.3 Melbourne Assessments (MUUL/MA2)

There were two assessments based upon the same activities and recorded data; the MUUL [95] and its successor the MA2 [81]. They are essentially the same, the MA2 being a development of the MUUL. This assessment is based around game play, providing the participant with a set of challenges in an interesting, though largely static environment. The test could be likened to an elaborate board game that a participant plays against itself with support and direction from the therapist. Success at each stage is rewarded with encouragement and treats. For example, successfully moving or opening a tube containing sweets allowed the participant to eat the sweets. The test was conceived as an assessment of ADLs, particularly for CP patients and has been successfully compared and reviewed against other similar assessments. Whilst it is a test of general ability with ADLs and uses both hands the assessments, as observed, concentrated on using the non-dominant hand although the dominant hand was also used. It should be noted that most patient participants were able to carry out some tasks with their non-dominant hand.

The whole assessment requires considerable interaction with the participant by a trained therapist and also required notable physical intervention to set up or reset challenges. There is a good variety of challenges that most participants respond to well. The overall scoring system is bespoke to the design of the game and may be difficult to associate with the actual movements or tasks carried out by the different participants. It is therefore, a subjective scale, though well correlated with other assessments in children and adolescents. Therapist interpretation is always a consideration with such assessments and the results between therapists (inter-rater scoring) may be subject to variation, although all trials are videoed and can be reassessed independently. Investigations of inter and intra-rater scoring has been mostly favourable [95].

The MUUL/MA2 of is a comprehensive evaluation tool that measures upper limb function in children (age 5-15) with neurological disorders. It comprises sixteen test items which require the use of one or both hands to reach, grasp, release, manipulate and transfer objects as well as drawing and promoting hand to mouth movements. It appears as a game with simple elements and typically takes 20-30 minutes to perform. There are rewards for participants as they progress and no particular attention is paid to, or commentary made regarding, any poor performance or failures. If a participant cannot complete a task, the next task is started without notable interruption.

A trained therapist conducts the test, providing instruction, encouragement and demonstration. It is videoed and requires a further 30 minutes to score on 37 sub-score assessments using a 3, 4, or 5-point rating. The maximum score is 120 and this is converted to a percentage which is normally reported. The dominant or unaffected hand is not assessed directly but anecdotal evidence suggests that a score of 95-100% would be typical. It is possible that a normal participant would obtain 100% with considerable ease compared to a patient participant using their dominant hand as there are observable differences in coordination and speed for most patient participants.

During clinical observations, the assessment, whilst clearly interesting to the observed participants, was tiring for most as it took a long (typically 20-30 minutes) time to complete. Despite careful pacing of the activities, early task failures appeared to de-motivate some participants. No score or achievement rating was provided to the participants although the therapist provided good encouragement and some of the games provided rewards.

5.1.4 Tyneside Peg Test (TPT)

At the time of writing, the TPT had not been widely reported but was inspired by the NHPT which has been used extensively in a variety of applications from assessing cognitive and physical ability to investigating mental impairment. It is essentially a test of finger dexterity but also requires gross arm movements when relocating the pegs and hence, can be considered a general test for assessing upper limb ability.

The TPT identifies the time taken to move nine pegs on a 3x3 grid from a starting board to a matching target board. The boards were approximately 250 mm square with the holes spaced evenly over this area. The pattern/order of peg movement is not prescribed and the participant can choose how they wish to proceed. The instructions given were for the patient to move the pegs from the starting board to the finishing board as quickly as possible. Timings were recorded electronically using sensors in both boards. Three different sizes of pegs and matching holes were used and movements from left to right and right to left were attempted. The pegs were made from nylon and weighed between 25 and 75 grams.

The time to move all nine pegs is a measure of ability howsoever the participant manages to achieve this objective. The participant's ability to grasp and manipulate the pegs is a fundamental requirement to completing the test. Handgrip dynamometer tests were conducted by the therapist as part of a general assessment before each session and it was noted that some patient participants showed little or no grip strength; indicated as zero or momentary deflection on the dynamometer whereas a healthy grip might typically be 50-250 N in the participant age range.

There were a number of problems with gripping the pegs, removing them from the starting board and placing them in the finishing board, particularly with the "small" and "medium" pegs. Some pegs were dropped and the test had to be restarted or the therapist helped the patient to start again by replacing the peg. The tests were largely successful on first attempt when patients used their dominant hand. Achievements with the non-dominant hand were more varied and some tests were not completed. In order to permit comparison, two different measures were recorded – time to complete the test for the dominant hand and additionally for the non-dominant hand the number of pegs successfully transferred.

The therapist administered the test, providing basic instructions and occasional support. The test is repeated up to nine times in each session using the three different peg and hole sizes and movement directions. The tests can take 10-20 minutes to set up and complete. Analysis is bespoke to the trial but would typically require a further 5-10 minutes to access and process the data files produced. No score or achievement rating was provided to the participants although the therapist provided good encouragement and completing the peg transfer was an obvious achievement. It was clear that the failure to complete the test with the non-dominant hand was of considerable disappointment to many of the participants, especially if preceded by the dominant hand.

Due to the significant number of patient participants who failed to move the "small" and "medium" sized pegs the only reliable data produced was for the "large" pegs and even here some participants could not complete the test. Hence, although some data does exist for the full range of tests, only the "large" peg tests are compared with the MUUL/MA2 and prototype 1 parameters.

It is notable that the TPT continues to be developed and now includes additional challenges of dexterity that were not featured in the contemporaneous tests with prototype 1.

5.1.5 Prototype 1 Fan-game

The prototype 1 device employed a standard fan-game devised by the author, as noted in section 4.2.4 and illustrated in Figure 5-5. Where practicable, all participants were tested with their dominant (D) hand first and then their non-dominant (ND) hand (paretic hand for the patient group). The only testing difference between the two groups was the venue and the use of a separate LCD screen for the patient group rather than a laptop screen. The two screens were of similar sizes (15.4" for patient and 15.1" for normal; both 4:3 aspect ratio). The patient group was assessed in the hospital whilst the normal group were assessed in a domestic setting. The choice of dominant hand was made by the normal participants and generally related to the hand they most often used for a PC mouse. For the patient group this was decided by the therapist based upon their known hemiplegia.

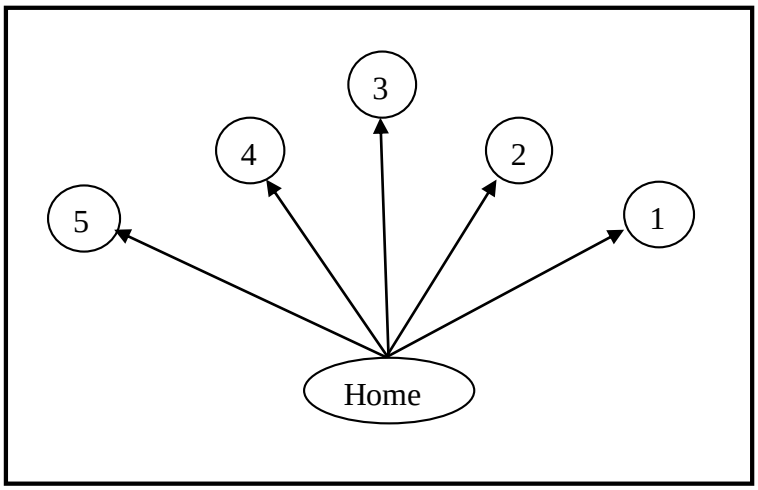


Figure 5-5 Basic Fan-game: Five Targets and Home Base

Instructions to all participants were standardized with all participants being instructed by the same therapist. Each participant sat at a table with the device and screen in front of them as illustrated in Figure 5-4. The therapist adjusted the height of the table and chair position to suit the patient participants and confirmed that all participants were seated comfortably and able to reach the skate and extents of the fan-game playing area.

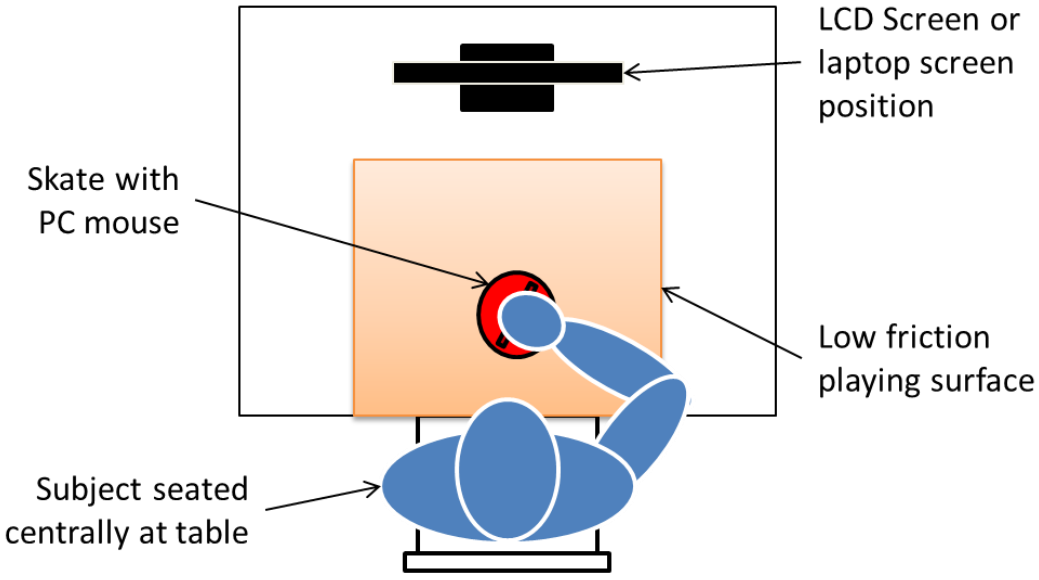


Figure 5-4 Schematic Experimental Setup

Standard instructions were provided to the therapist for reference when introducing each participant and in setting up the fan-game (see appendix 5.A). Each participant attempted the fan-game five times forming a game-set with potentially 25 paths to the targets. Prior to recording the results, each participant was given clear instructions (see appendix 5.B) and they attempted a trial fan-game of five targets to gain familiarity with the device and to allow the therapist to see if there were any particular issues. None were noted.

The objective of the fan-game was to move the cursor (a blue smiley face) to hit targets (red sad faces) from a common home base (green semi-circle). Five targets were arranged at the distances and angles noted in section 5.2 from the home base with approximately 1:1 scaling between the mouse movement on the playing surface and cursor movement on the screen.

When a target was hit an explosion sound was played and the target disappeared. The trigger point for a hit was set as 50 percent overlap of the cursor on the target as noted in section 4.4.1. After each target was hit the participant moved the mouse back to the home base. When the home was reached, (defined as a similar overlapping of the cursor with the home) the next target appeared and the game continued until all five targets were removed.

Where practicable, the participants were tested with their dominant hand first for a full game-set and then their non-dominant hand was used for a similar game-set. Whilst the therapist knew that the games were identical, the participants did not.

Having completed one fan-game, the next pattern of targets, as shown in Table 5-1 (see section 4.4.1) was presented and so on until all five games were complete, which typically took between five and ten minutes. The simple setup allowed for easy transfer of tasks between hands.

Table 5-1 Target Presentation Order in each Game (see Figure 5-6)

Game	First	Second	Third	Fourth	Fifth
1	1	2	3	4	5
2	2	4	1	5	3
3	5	1	4	3	2
4	3	5	2	1	4
5	2	3	4	5	1

Video data was required for all patient participants as part of the MUUL/MA2 assessment. The same recording system was used for the patient participant TPT assessments and the game. Unfortunately, all of the video data was lost or corrupted.

Assessments with prototype 1 were attempted after the MUUL/MA2 and TPT assessments had been conducted and were completed in the same session. All patient participants appeared to approach the game with renewed enthusiasm following the lengthy MUUL/MA2 and TPT testing during which some fatigue was evident. All participants completed the fan-games without apparent fatigue. The most notable difference between the assessments is that prototype 1 presented a mouse-based game which was a very familiar concept to participants who use computers regularly. Also, the game required limited therapist intervention after such intensive clinical sessions and may have been viewed by the participants as more like playing than testing.

Each attempt at a fan-game (five targets) required approximately one minute to set up and up to three minutes to complete. Although no score was given, all participants were able to complete the game and it was obvious that they had achieved the required goal of reaching the five targets. Five fan-games were attempted and all participants reached all targets in each fan-game.

5.2 Participant Data and Game-set Measurements

The patient data used to establish the new metric is all baseline data gathered prior to any clinical intervention. Table 5-2 summarises the participant data for the normal (control) and patient groups. Each participant attempted the fan-game using their dominant (D) and non-dominant (ND) hand. The game-set data were used to extract the parameters, as noted in section 3.3 and described in Figure 5-6.

Table 5-2 Main Patient and Normal Participant Summary Data – Initial Data

Data	Normal	Patient
Size (N)	11	12 (plus 3 follow up results)
Age at test	7y0m to 12y8m; (mean = 10y10m SD = 1y5m)	6y3m to 18y0m (mean = 10y9m SD = 3y2m)
Sex	5M/6F	7M/5F
Hand used	dominant and non-dominant	dominant and paretic (non-dominant)
Fan-games	54 (1 corrupted)	58 (2 corrupted)
Paths	543 (7 corrupted)	588 (12 corrupted)
MUUL/MA2 tests	n/a	12 (Paretic only) (plus 3 follow up)
TPT tests	11	12 dominant; 8 non-dominant

As reported in section 5.3.1, participant outliers were noted in both participant groups and these were removed (ID: M and AH in appendix 5C). The resultant participants and corresponding game data are shown in Table 5-3. Boxplots of TPT data before and after removal of the two participant outliers are shown in appendix 5D.

Table 5-3 Main Patient and Normal Participant Summary Data – Trimmed Data

Data	Normal	Patient
Size (N)	10	11 (plus 3 follow up results)
Age at test	10y2m to 12y7m; (mean = 11y2m SD = 0y8m)	7y8m to 18y0m (mean = 11y1m SD = 3y0m)
Sex	4M/6F	6M/5F
Hand used	dominant and non-dominant	dominant and paretic (non-dominant)
Fan-games	49 (1 corrupted)	53 (2 corrupted)
Paths	494 (6 corrupted)	539 (11 corrupted)
MUUL/MA2 tests	n/a	11 (paretic only)
TPT tests	10 dominant and non-dominant	11 dominant; 8 non-dominant

The data acquisition system was not fully tested at the time of the trial and some data was corrupted or distorted in the raw format obtained from the mouse, as described in section 4.4.6. This resulted in the loss of some whole fan-game datasets, and some individual path data as noted in Table 5-3.

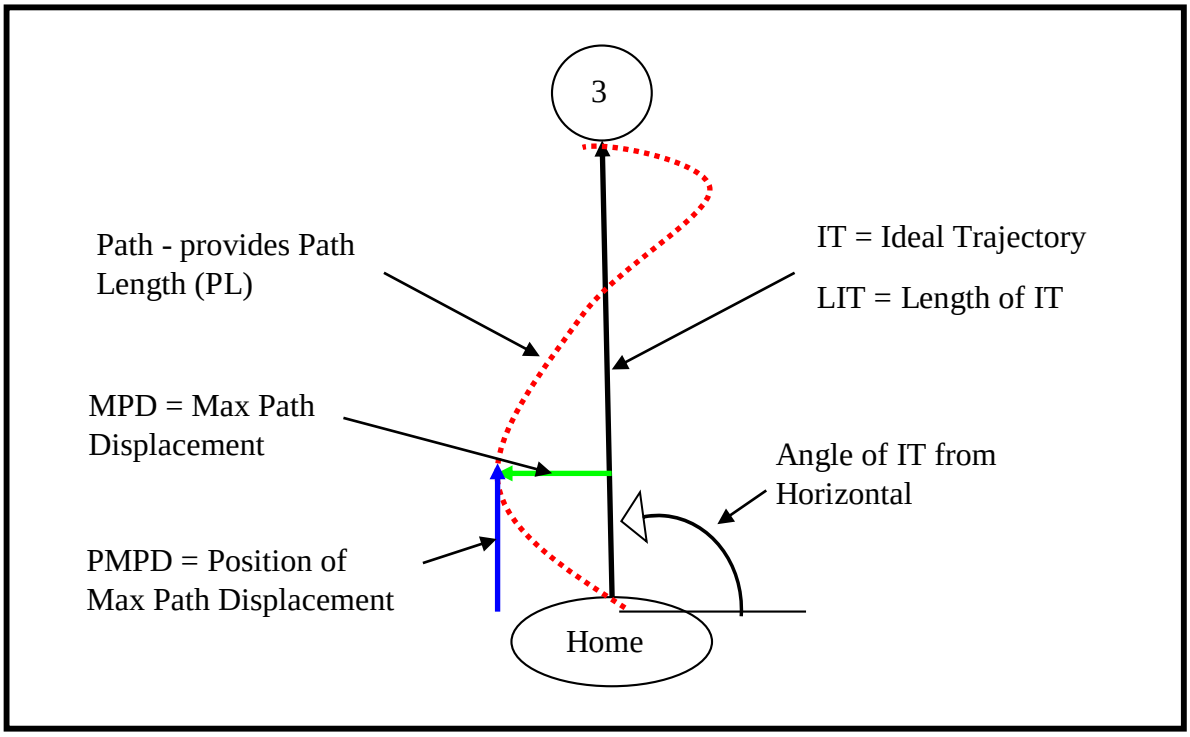


Figure 5-6 Principal Measurements Derived from Raw XY Mouse Data

For the patient participants, TPT assessment data was collected for both hands although three of the patient participants were unable to complete the TPT with their non-dominant hand. Although both hands may be used for some tasks in the MUUL/MA2 tests, the assessment only really applies to the paretic hand as it affects daily activities, as noted in chapter 3. The participant data, clinical assessment data and processed game data summaries are contained in Appendix 5C.

The path length (PL) data recorded by the software and noted in these results were checked against actual path lengths on the playing surface. Over a number of pre-and post-test calibrations, the measured direct line path was within 1 mm of that calculated from the software. The ratio of long to short trajectories was intended to be 1.5. Full details are contained in appendix 4A.

Trajectory angles were set in the software, as noted in section 4.4.1, nominally 30 degrees apart measured anticlockwise from the horizontal plane. The values are reproduced in Table 5-4 together with the calculated lengths and angles taken from the XY positional data recorded for each game-set. This shows that onscreen trajectories closely matched those planned and were within 2% of planned IT length and three degrees of planned IT angle.

Table 5-4 Calibration Target Trajectories Relative to Home Base					
Planned and Measured Target Details	**1**	**2**	**3**	**4**	**5**
Planned Length of IT (mm) from Software	180	120	180	120	180
Measured Length of IT (mm) from screen	177	118	177	118	177
Planned Angle of IT from horizontal from software (degrees)	30	60	90	120	150
Calculated Angle of IT from horizontal (degrees)	27	58	90	122	153

Time checks were carried out to ensure that clock speeds were being converted accurately to game durations. These were assessed over a larger period of time than that required by a typical game (one to two minutes) to minimise errors in synchronising with the PC clock. Time checks showed that timing data from the software was consistent with that recorded. Full details are contained in appendix 4A.

All absolute and relative parameter data was derived from positional and/or temporal data noted earlier and hence is of similar accuracy to the source data. The instantaneous velocity taken from the rotated path data was stored and further analysed with the intention of extracting a simple estimate of instantaneous velocity where possible. There were notable problems with such extraction and this is discussed in detail in section 3.4. At the time of these trials such derived parameters were discounted as they were too variable in quality to be reliable although their potential is obvious. Some of these limitations were investigated further in preparation for prototype 2 using numerical methods and these are discussed in appendix 3B.

Raw positional data from the start of the game at the home base to reaching the final target was recorded at approximately 10 ms intervals (see section 4.2.4). The data from the home base to each target was the main movement of interest. This information was extracted from the bulk data for further processing. The return data (from target to home) was only recorded for the first four trajectories. There are limits to the usefulness of such data as the home target became a familiar objective after a few games and presents a repetitive task to the participants. In contrast the designated targets appeared to the participants in an unknown manner (but predetermined and consistent sequence) which provided an unpredictable challenge.

To minimize inconsistencies between tests, the start point within the data sets was standardized as the start of continued motion (in any direction) after the cursor had passed within a fixed radius of the Home base.

5.3 Statistical Analysis

The stated value for significance testing is taken as $\alpha = 0.05$ and this is used throughout the statistical analysis, being a reasonable standard for the measurements noted herein. All statistical tests were carried out using SPSS [178] unless noted otherwise.

5.3.1 Normality of Data

Most of the statistical tests required in this thesis presume normality in the data under examination. Tests for normality were conducted on the clinical assessments to confirm suitability of any parametric correlations. The Shapiro-Wilk test assumes the null hypothesis that the data are normally distributed and is appropriate for small samples ($N<50$) and hence is the most suitable test for the data obtained. With the size of samples obtained ($N<12$) it was noted that the test is very sensitive to a single outlier and such outliers were identified in each participant group.

Boxplots of the TPT data are shown in appendix and this identifies potential outliers. With these included, the data did not satisfy the threshold of $p>0.05$. Upon removal, all clinical data satisfied the Shapiro-Wilk test as noted in Table 5-5. The results indicate that the clinical data for all sub-groups are can be considered as being normally distributed ($p>0.05$) and hence parametric correlation tests are valid.

Table 5-5 Shapiro-Wilk Normality Test: All Participants - Clinical Scales

Clinical Data	Dominant			Non-dominant		
	N	Statistic	Sig	N	Statistic	Sig
TPT ((normal)	10	0.92	0.400	10	0.97	0.889
TPT (patient)	11	0.91	0.213	8	0.82	0.052
MUUL (patient)	n/a	n/a	n/a	11	0.89	0.255
MA2 (patient)	n/a	n/a	n/a	11	0.93	0.397

Notes:
MUUL and MA2 only apply to the non-dominant hand for patient participants
One participant from each group was removed as an outlier.
Not all patient participants completed the TPT with their non-dominant hand.

The proposed fan-game parameters were assed for normality using the same test and the results are shown in Table 5-6 and Table 5-7.

Table 5-6 Shapiro-Wilk Normality Test: Normal Participants - Fan-game Parameters

Parameters	Dominant			Non-dominant		
	N	Statistic	Sig	N	Statistic	Sig
PL / LIT	10	0.80	0.014	10	0.80	0.014
PL / PT	10	0.98	0.977	10	0.97	0.900
LIT / PT	10	0.96	0.766	10	0.95	0.658
MPD / PL	10	0.88	0.116	10	0.95	0.710
MPD / LIT	10	0.89	0.177	10	0.97	0.899
TDA / LIT	10	0.82	0.023	10	0.92	0.387
TDA / PL	10	0.89	0.148	10	0.96	0.770
MDLoT / LIT	10	0.94	0.540	10	0.80	0.014
PMPD / LIT	10	0.95	0.656	10	0.95	0.671
ALHS / LIT	10	0.85	0.053	10	0.89	0.150
ARHS / LIT	10	0.71	0.001	10	0.86	0.086
NA / LIT	10	0.92	0.378	10	0.92	0.366

Notes:
One participant from each group was removed as an outlier.
See section 3.3 for parameter descriptions.

Table 5-7 Shapiro-Wilk Normality Test: Patient Participants - Fan-game Parameters

Parameters	Dominant			Non-dominant		
	N	Statistic	Sig	N	Statistic	Sig
PL / LIT	11	0.78	0.006	11	0.84	0.036
PL / PT	11	0.91	0.274	11	0.87	0.069
LIT / PT	11	0.94	0.564	11	0.94	0.536
MPD / PL	11	0.88	0.103	11	0.95	0.615
MPD / LIT	11	0.93	0.386	11	0.95	0.611
TDA / LIT	11	0.98	0.983	11	0.87	0.087
TDA / PL	11	0.91	0.219	11	0.97	0.868
MDLoT / LIT	11	0.87	0.066	11	0.83	0.024
PMPD / LIT	11	0.92	0.314	11	0.96	0.734
ALHS / LIT	11	0.83	0.026	11	0.90	0.208
ARHS / LIT	11	0.91	0.270	11	0.95	0.367
NA / LIT	11	0.92	0.303	11	0.98	0.928

Notes:
One participant from each group was removed as an outlier.
Not all patient participants completed the TPT with their non-dominant hand.
See section 3.3 for parameter descriptions.

Whilst the majority of the parameters satisfy the conditions for normality, those with shaded values do not meet the required level of p>0.05 and hence statistics from any parametric correlations should be used with caution. The planned use of regression and PCA techniques is not precluded by the potential lack of normality in some parameters. However, those parameters not meeting the normality criteria were excluded as noted in section 5.5.

The boxplots in Figure 5-7 and Figure 5-8 show the two absolute parameters of path time (PT) and path length (PL) to indicate the type of data used as the basis for the relative parameters used to form the new metric. There are notable outliers and relatively wide interquartile ranges and extensive whiskers.

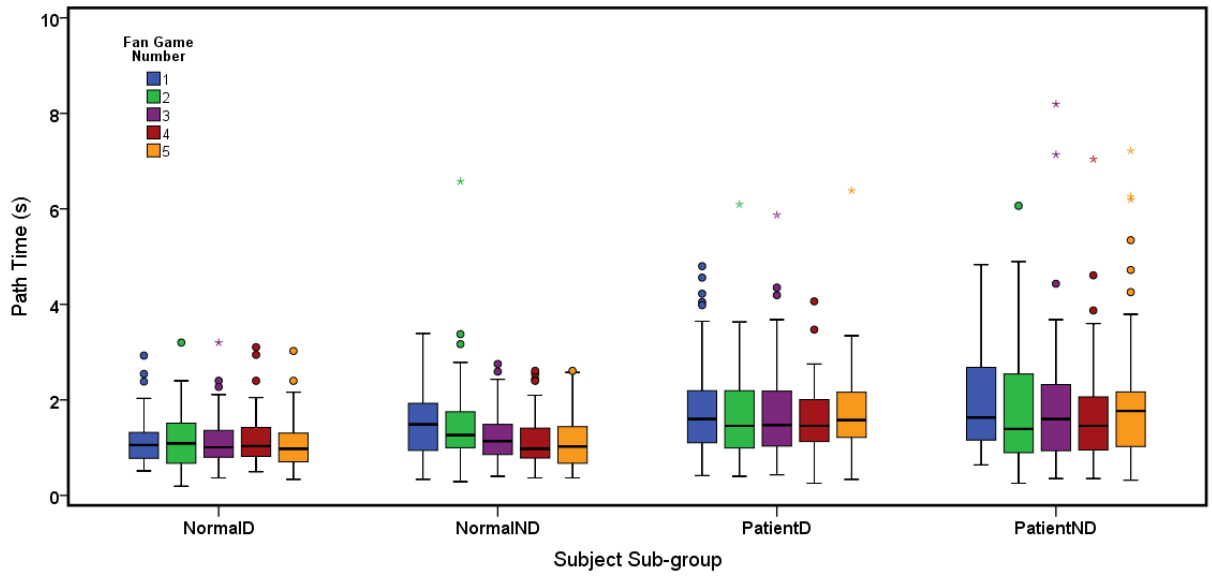


Figure 5-7 Boxplot of Path Time for each Fan-game by Sub-group

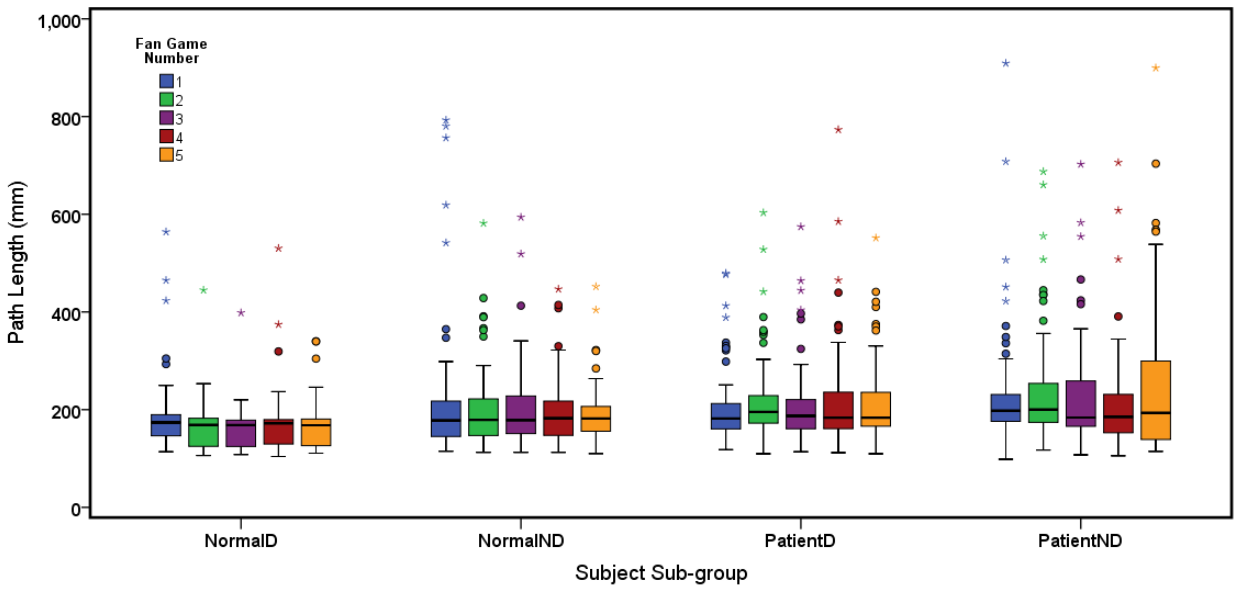


Figure 5-8 Boxplot of Path Length for each Fan-game by Sub-group

Boxplots of all pre-selected parameters are included in appendix 5.E. A selection of these are shown in Figure 5-10, Figure 5-9 and Figure 5-11 to illustrate the type and range of data under consideration. As noted in section 5.1 the median values (black horizontal bar in boxplots) were used in all subsequent analysis and assessment.

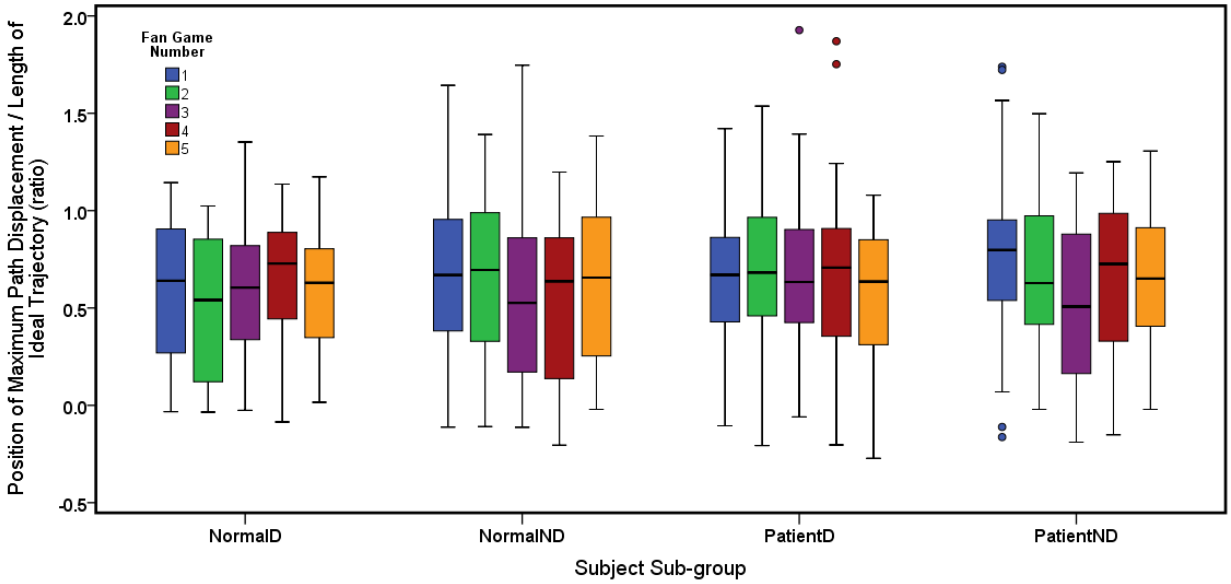


Figure 5-9 Boxplot of Relative Parameter PMPD/LIT for each Fan-game by Sub-group

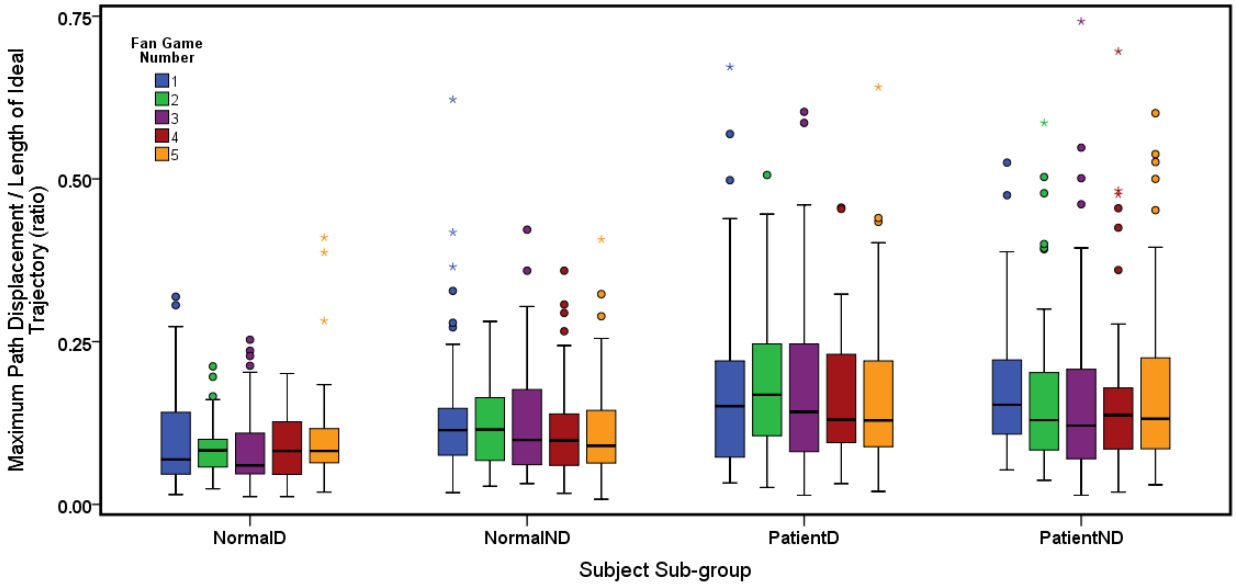


Figure 5-10 Boxplot of Relative Parameter MPD/LIT for each Fan-game by Sub-group

It was anticipated that the parameters would show improvement in ability (smaller PT, lower MPD/LIT, etc) as the fan-games progressed from 1 to 5 but this was not always observed for all participants and all parameters under consideration. However, the trend for lower performance from normal dominant to patient non-dominant is generally observed. Notably,

the value of PMPD/LIT was quite consistent across sub-groups with few extreme values compared to most other parameters as seen in Figure 5-9. As noted in section 6.1 this may be a subtle feature of the planned trajectories.

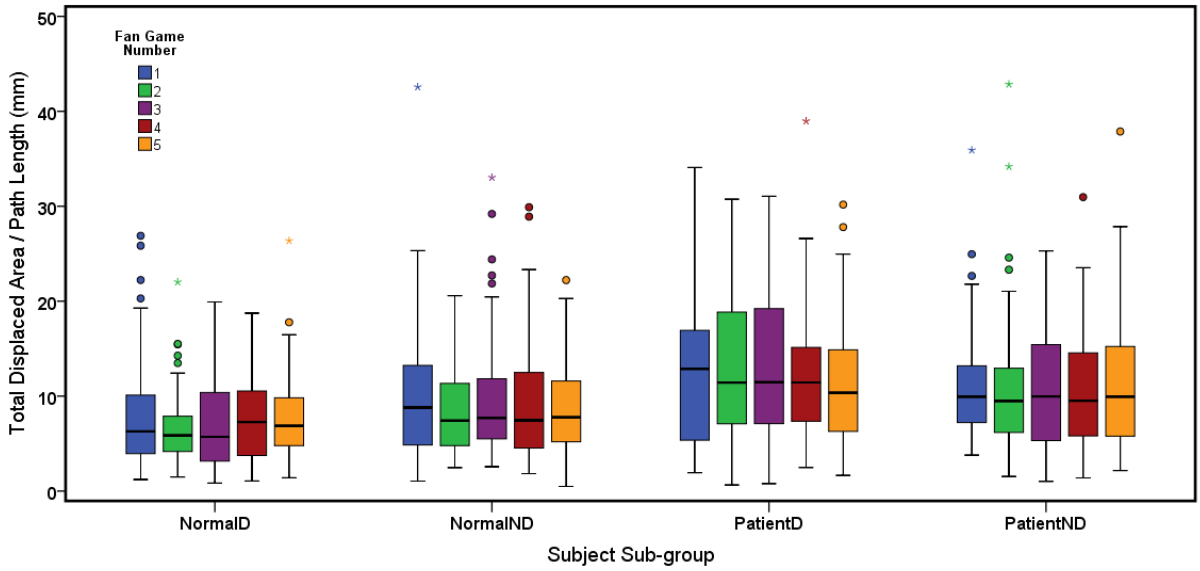


Figure 5-11 Boxplot of Relative Parameter TDA/PL for each Fan-game by Sub-group

5.3.2 Parametric Correlations – Clinical Scales

The results for the two clinical assessments (averaged TPT and summary MUUL/MA2) were compared to see if these two scales were related. This comparison had not been carried out by the clinical team and was of interest in assessing any potential new metric against known scales. All data are final MUUL/MA2 composite scores or averaged TPT times for both (large pegs: l-r and r-l) hands. The full set of assessment data (TPT original data and MUUL/MA2 sub-scales) obtained from the clinical team is contained in appendix 5A.

The MUUL/MA2 assessments are only really applicable to the non-dominant hand although some tasks are bi-manual and participants were not always constrained to using only one hand when performing the tasks. A consistent score of between 95 and 100 would be anticipated for the dominant hand for each participant (range suggested by the therapist conducting the trial).

From the data in Table 5-8 it can be concluded that a moderate correlations exists between the MUUL/MA2 assessments and the TPT times for the dominant and non-dominant hand indicating some relationship between these scales as suggested in section 1.5. The MUUL and MA2 scores were very similar which is predictable given that they are determined in a similar way from identical video data. As expected correlations between MUUL and MA2 scores are very high ($r > 0.9$, $p < 0.001$) reflecting the nature of the data. The negative correlation confirms that a high MUUL/MA2 score relates to a low TPT time.

Table 5-8 Pearson Correlation r: Patient Participants - TPT, MUUL, MA2

Clinical Data	Dominant			Non-dominant		
	N	Statistic	Sig	N	Statistic	Sig
MUUL to	n/a	n/a	n/a	11	0.998	0.000
TPT to	11	-0.409	0.211	8	-0.458	0.254
TPT to MA2	11	-0.386	0.242	8	-0.396	0.334

Notes:
MUUL and MA2 are primarily assessments of the non-dominant hand but some tasks might be bi-manual.
For the purposes of this thesis, correlation coefficients (absolute values) are categorised [183] as follows:
Weak: <= 0.35; Moderate: 0.36 to 0.67; Strong: 0.68 to 0.89; Very high: 0.9 to 1.0.
Shaded cells indicate significant correlations.
Not all patient participants completed the TPT with their non-dominant hand.

The TPT assessment was the only clinical test conducted (and relevant) for normal participants. The data in Table 5-9 shows strong positive correlation between the dominant and non-dominant hands for the TPT times obtained from normal participants. This is consistent with the observations of most normal participants using this device or similar devices such as a PC mouse. It is notable that no such correlation exists for the corresponding patient TPT times. In fact there is a negative weak correlations which was not anticipated. This may be influenced by the small data set (N=8) as three participants found the test too difficult to complete.

Table 5-9 Pearson Correlation r: All Participants - TPT

Clinical Data	Dominant to Non-dominant		
	N	Statistic	Sig
TPT Dominant to Non-dominant: Normal	11	0.638	0.047
TPT Dominant to Non-dominant: Patient	8	-0.307	0.460

Notes:
For the purposes of this thesis, correlation coefficients (absolute values) are categorised [183] as follows:
Weak: <= 0.35; Moderate: 0.36 to 0.67; Strong: 0.68 to 0.89; Very high: 0.9 to 1.0.
Not all patient participants completed the TPT with their non-dominant hand.

5.4 Graphical Comparison of Sub-groups Parameters

A number of visual comparisons were carried out to identify any potential patterns of behaviour between the participant groups. This also allowed early detection of anomalous results that might not have been identified using common statistical measures.

The raw path data was provided as X and Y values for each path in each fan-game and this was processed in MATLAB™ to extract parameters and permit data visualisation, as shown in Figure 5-2. The paths for each fan-game were plotted on common axes to illustrate the movements made by the participants with the skate. These paths were also rotated to a common horizontal axis to allow visualisation of overlaid paths permitting observation of the paths against a trajectory normalised to the horizontal axis.

5.4.1 Normal and Patient Participant Paths

Typical paths taken from the MATLAB™ post-processing stage are contained in Figure 5-12 to Figure 5-15 which show paths for both patient and normal participants. Whilst these graphs are illustrative of the many reviewed, they show interesting differences in the paths followed. The participants in these graphs were chosen to be the same sex, of similar age (patient: 9 y, 4 m; normal: 11 y, 0 m) and they obtained similar scores in the TPT with their dominant hand (patient: left hand: 12.5 s; normal: right hand: 12.6 s). The trajectories indicated at "Traj 1-5" in the legend show the orientations and lengths of the ideal trajectories for each target.

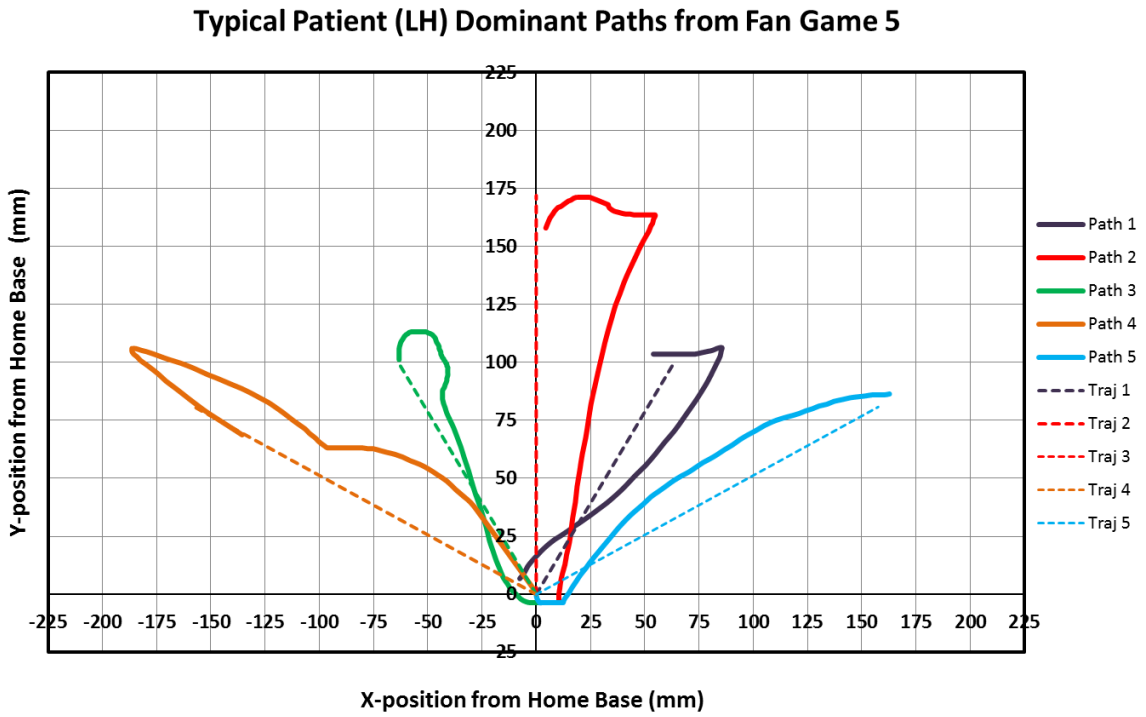


Figure 5-12 Typical Patient Participant Paths – Dominant Hand

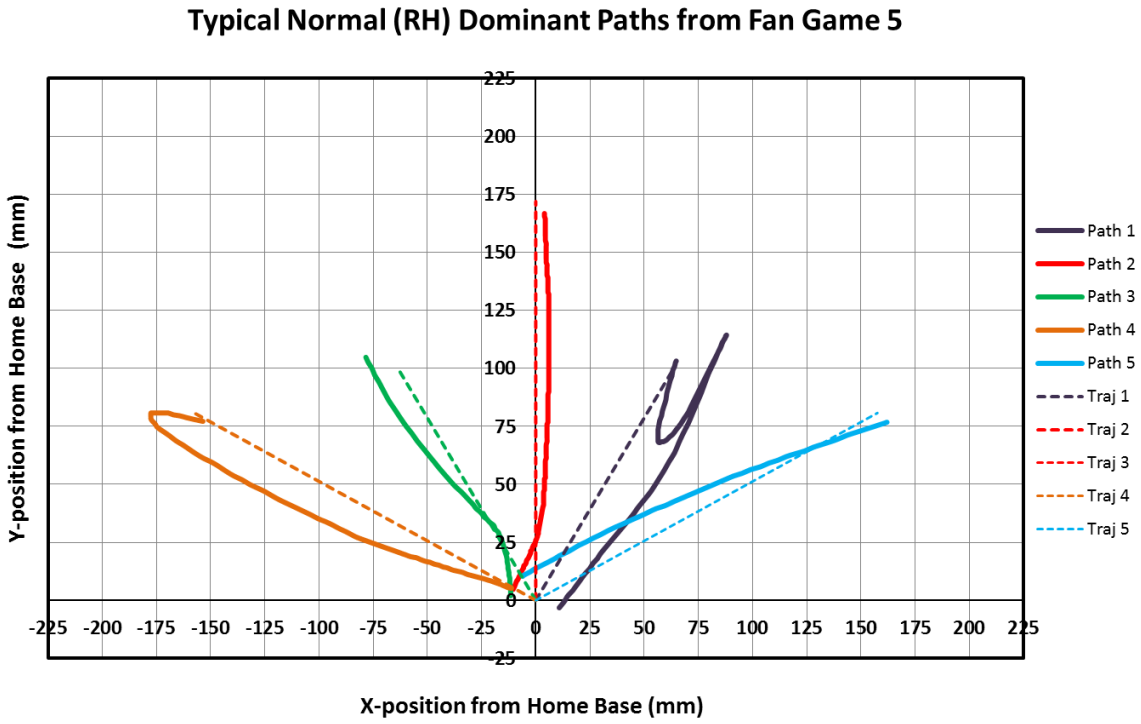


Figure 5-14 Typical Normal Participant Paths – Dominant Hand

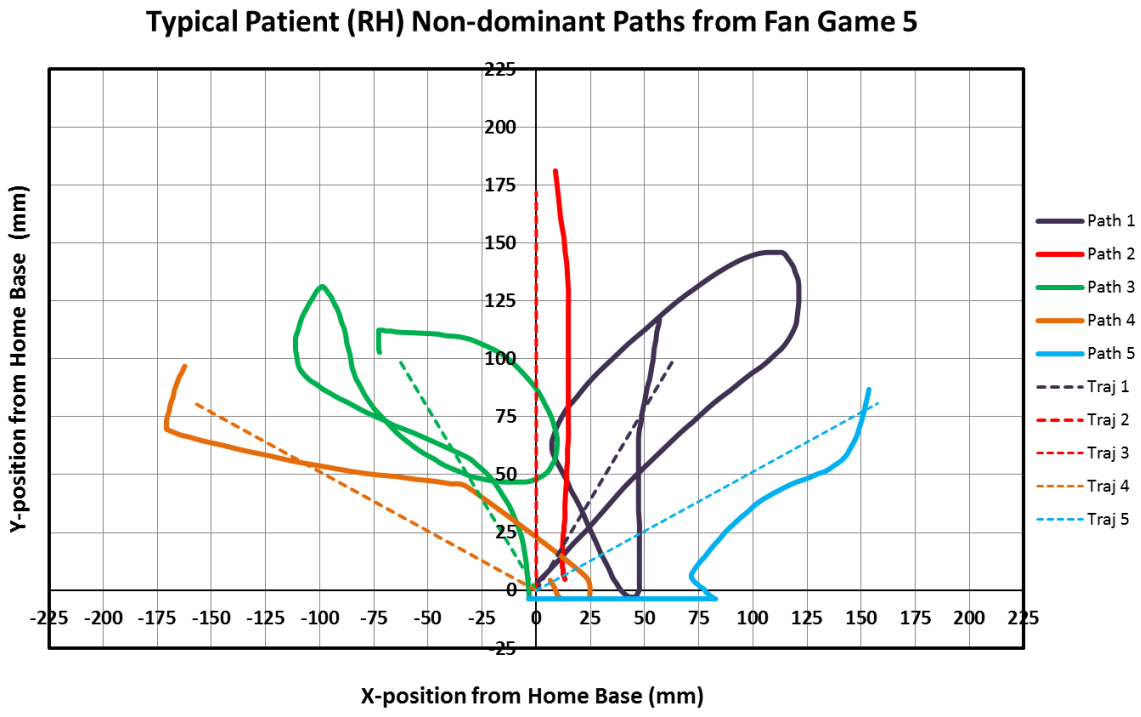


Figure 5-13 Typical Patient Participant Paths – Non-dominant Hand

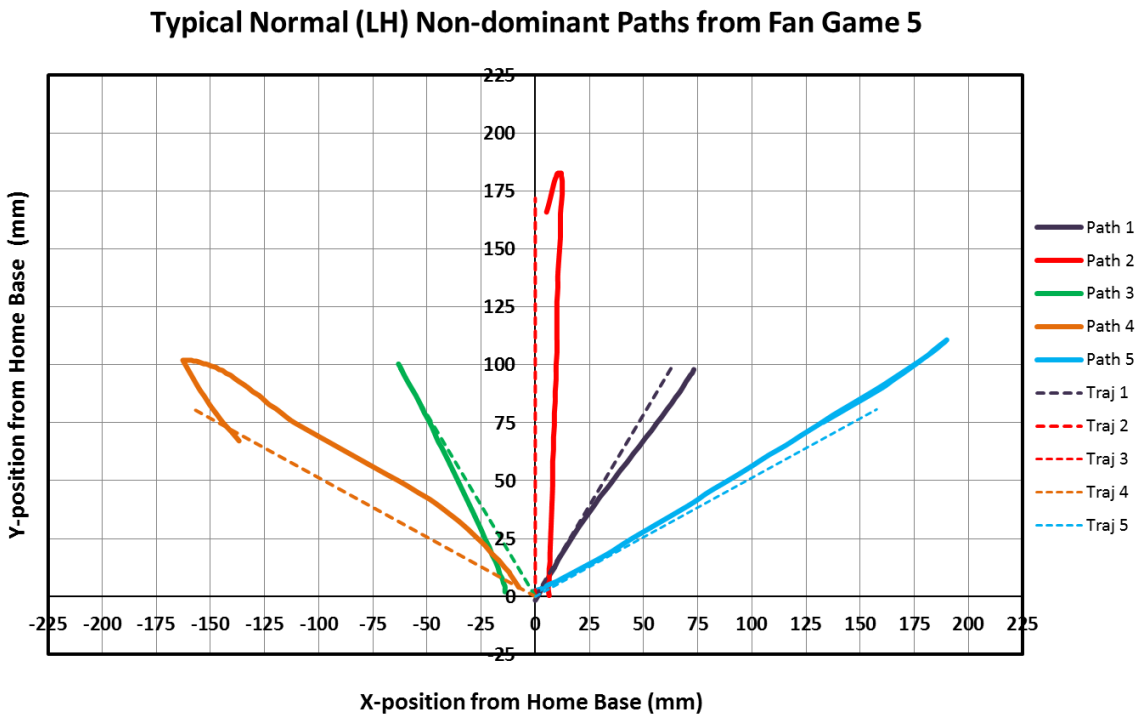


Figure 5-15 Typical Normal Participant Paths – Non-dominant Hand

The graphs show typical differences in reaching ability indicated by longer and less efficient paths for patient participants compared with those for normal participants. Some of the normal participants exhibited greater variations in their paths than indicated in Figure 5-14 and Figure 5-15 and similarly some of the patient participants demonstrated more control than that shown in Figure 5-13. However, patient participants typically presented pathways that were longer, contained more changes of direction and were more varied in path shape than those for normal participants. The differences between dominant and non-dominant hands was typically not so marked for normal participants as for patient participants as noted in the boxplots in appendix 5E.

5.4.2 Comparisons of Parameters

A selection of potential parameters to form a new metric was made based upon two separate processes; basic parametric correlations with the TPT scores and factor reduction, as noted in Figure 5-2. This process identified parameters which were not normally distributed and hence could not be reliably used in any further correlations needed to form a new metric. It also identified groupings of parameters which appeared to be dominant within a sub-group and might be indicative of movement components such as those indicated in section 1.5, namely movement efficiency (ME), movement accuracy (MA) and movement laterality (ML). As noted previously, these were not intended to be definitive components for all sub-groups, rather they were anticipated to be indicators of trends in ability across the sub-groups. Hence, the relative values of the PCA were used to help identify parameters which might be common to all four sub-groups and hence which might be combined reliably to form a new metric.

All selected parameters were plotted against the trajectory angles used in the standard game. This provided a common baseline for comparing paths followed and allowed a rapid visual comparison of participant performance. The full complement of these graphs is stored digitally in a separate file.

5.4.3 Classification of Parameters

The pre-selected parameters established in section 3.3 are reproduced in Table 5-10.These parameters formed the basis of comparisons across data sets and sub-groups and the clinical scales. All parameter values were taken from the median values of the five game-sets. Data for each sub-group were visually compared for each parameter by trajectory, game-set and by dominant and non-dominant hand. Patterns of data emerged which indicated distinctive patterns of behaviour between sub-groups and these helped to inform the classifications noted below.

The significance of any classification may depend upon the progress of a condition, a participant's general health or environment and degree of engagement with the assessment. Initial movement classifications were introduced in section 3.3 and tentatively described as potential indicators of movement efficiency (ME), movement accuracy (MA), and movement laterality (ML) or handedness. The initial assignments shown in Table 5-10 were qualitative but indicative of likely classifications of ability from the author's observation and limited available references in the literature. It is possible from the tables that ME and MA might be combined as a descriptor of path efficiency (inaccurate paths are rarely efficient) or more generally as movement control or ability. However, the potential of such descriptors is as yet unknown so they were retained for further investigation. These initial classifications were used to support selection of suitable parameters for the new metric and are not intended as definitive classifications across all sub-groups.

Table 5-10 Initial Movement Components for Pre-selected Parameters			
Parameter	**Movement Efficiency (ME)**	**Movement Accuracy (MA)**	**Movement Laterality (ML)**
Path Length / Length of Ideal Trajectory (ratio)	++	++	
Path Length / Path Time (mm/s)	+++	+	
Length of Ideal Trajectory / Path Time (mm)	+++	+	
Maximum Path Displacement / Path Length (ratio)	+	++	
Maximum Path Displacement / Length of Ideal Trajectory (ratio)	+	++	
Total Displaced Area / Length of Ideal Trajectory (mm)	++	+++	
Total Displaced Area / Path Length (mm)	++	+++	
Maximum Distance along line of Trajectory / Length of Ideal Trajectory (ratio)	+		
Position of Maximum Path Displacement / Length of Ideal Trajectory (ratio)	++		
Area to Left of Trajectory / Length of Ideal Trajectory (mm)	+	+	++
Area to Right of Trajectory / Length of Ideal Trajectory (mm)	+	+	++
Nett Area / Length of Ideal Trajectory (mm)	++	++	++
Notes: The symbols used indicate the author's anticipated classification and potential strength of association between the parameter and movement component. See section 3.3 for further explanation of parameters.			

The importance of movement laterality is probably related to handedness and is not fully understood in the literature. It was noted as being potentially significant in section and so was retained for further investigation and will be discussed in section 6.1.

5.5 Statistical Assessment of Parameters

Within the patient sub-groups, differences between hands were noted for most parameters and these were typically small compared to those noted between the patient and normal sub-groups. Some parameters such as MPD/LIT and TDA/PL are predictably smaller, indicating more efficient movements for normal participants. The values of PT/PL, a form of bulk speed, suggest that the patient participants spent more time in order to achieve greater accuracy but did not match the performance of normal participants with either hand.

5.5.1 Parameter Selection

Given that no single parameter could be identified as a metric of ability across all sub-groups, any new metric would probably be based upon the combination of multiple parameters, and these should be common to all sub-groups. In order to identify the most likely parameters relevant to a broad ability spectrum, a more robust method of selection was required than visualisation or using isolated statistics across parameters. A reduced data set of the most relevant parameters was required to test the statistical hypothesis with the available data in order to avoid over-fitting in any regression analysis. It was noted that using all twelve parameters in any regression analysis with the TPT resulted in perfect fits for each sub-group.

Although the primary objective of this thesis was to identify a potential new metric, it was equally important to develop a method for extending this approach to new data sets so that the new metric could be extended and developed as more participants used the system. Additionally, the ultimate objective of automating measurements in real-time precluded the use of elaborate manual comparisons of data or standard statistics.

As noted in section 5.1 two selection processes were used to try to identify suitable parameters to form a new metric having first satisfied the condition of normality. The first process used an initial principal component analysis (PCA) within SPSS™ based upon Varimax rotation and three components for each sub-group, the latter being indicated by the scree plots of eigenvalues of all components. The resulting components accounted for between 87% and 92% of the variance. A number of components were cross-loaded indicating that some parameters could be considered as contributing to more than one component. Where cross-loading occurred a single dominant component was recorded where its value was greater than two times any other component. Loadings below 0.2 were not recorded as they were considered insignificant. The output data is shown in appendix 5.F.

The second process used an IRA based upon the automatic linear modelling (ALM) function in SPSS™. This function was used to identify the contribution of each parameter to the combined fitting of the parameters against the TPT data within each sub-group. All relative parameters (see Table 5-10) for all sub-groups were entered without any weighting or trimming of data. The results indicated that a perfect fit was obtained with these twelve parameters and that predictably some contributed more than others to the fitted data. The parameters with the highest contribution (importance greater than 0.1) from ALM were chosen for further assessment in the new metric. The output data from the IRA is shown in appendix 5G.

It was anticipated that the results of the PCA would map to the movement quality components (ME/MA/ML) suggested in Table 5-10.Whilst there was clear mapping for normal

participants the patterns became less conspicuous across all sub-groups and could not be relied upon. It is possible that with more data sets such patterns may become evident.

It should be noted that all normal participants were naturally right-handed whereas patient participants had a mix of left and right hand dominance. There was insufficient data to extract separate PCA statistics for the left and right handed patient participants.

The summary results in Table 5-11 show the five parameters which satisfied normality checks, and contributed significantly to the initial regression analysis for at least two sub-groups, and possessed notable loading in the PCA without significant cross-loading. The exception is TDA/PL which did not really meet the cross-loading criterion as three components were noted for the normal dominant sub-group. It was included as it represented a valuable measure and the other similar parameter TDA/LIT was excluded due to concerns over normality of the data. The PCA was used as a largely qualitative measure of selecting parameters to identify potential movement quality components and hence was more indicative than decisive in this process.

The green shaded cells indicate that the parameter meets the requirements for each of the selection processes. The values indicated in the columns (relative importance) are taken from the IRA, see appendix 5G.

Parameters (highlighted parameters selected for new metric)	Satisfies Normality Checks (p>0.05)					Satifies Normality Checks and Number of Components Identified from PCA					Satifies Normality Checks and Relative Importance from Initial Regression Analysis					Select for New Metric
	Normal dominant	Normal Non-dominant	Patient Dominant	Patient Non-dominant	All sub-groups	Normal dominant	Normal Non-dominant	Patient Dominant	Patient Non-dominant	Meets Cross-loading Criteria	Normal dominant	Normal Non-dominant	Patient Dominant	Patient Non-dominant	Noted in more than two Sub-groups	
Tyneside Peg Test	Y	Y	Y	Y	Y	n/a	n/a	n/a	n/a	n/a					n/a	Y
MUUL	n/a	n/a	Y	Y	n/a	n/a	n/a	n/a	n/a	n/a					n/a	
MA2	n/a	n/a	Y	Y	n/a	n/a	n/a	n/a	n/a	n/a					n/a	
Path Length / Length of Ideal Trajectory (ratio)	N	N	N	N	N	2	1	3	1	N					N	
Path Length / Path Time (mm/s)	Y	Y	Y	Y	Y	1	1	2	2	Y	0.01	0.12	0.10	0.26	Y	Y
Length of Ideal Trajectory / Path Time (mm)	Y	Y	Y	Y	Y	1	1	2	1	Y	0.00	0.20	0.11	0.25	Y	Y
Maximum Path Displacement / Path Length (ratio)	Y	Y	Y	Y	Y	1	1	1	3	N	0.16	0.07	0.12	0.06	Y	
Maximum Path Displacement / Length of Ideal Trajectory (ratio)	Y	Y	Y	Y	Y	1	2	2	1	Y	0.05	0.07	0.11	0.20	Y	Y
Total Displaced Area / Length of Ideal Trajectory (mm)	N	Y	Y	Y	N	1	1	2	1	N					N	
Total Displaced Area / Path Length (mm)	Y	Y	Y	Y	Y	1	3	2	1	N	0.11	0.07	0.11	0.04	Y	Y
Maximum Distance along line of Trajectory / Length of Ideal Trajectory (ratio)	Y	N	Y	N	N	1	1	1	1	N					N	
Position of Maximum Path Displacement / Length of Ideal Trajectory (ratio)	Y	Y	Y	Y	Y	2	1	1	2	Y	0.47	0.07	0.05		Y	Y
Area to Left of Trajectory / Length of Ideal Trajectory (mm)	N	Y	N	Y	N	1	1	3	1	N					N	
Area to Right of Trajectory / Length of Ideal Trajectory (mm)	N	Y	Y	Y	N	2	1	1	2	N					N	
Net Area / Length of Ideal Trajectory (mm)	Y	Y	Y	Y	Y	1	2	1	1	Y	not indicated	not indicated	not indicated	not indicated	not indicated	

Table 5-11 Parameter Selection Summary

5.5.2 Basis for a New Metric

It is clear from the preceding sections that that no dominant parameter from the twelve pre-selected relative parameters was identified in the statistics, PCA or initial regression analyses that were conducted for each sub-group. Whilst some of the parameters correlated reasonably well, consistent predictions could not be made for any sub-group based upon a single parameter and hence none could be used across all sub-groups.

As noted in section 1.5, it was anticipated that the relative importance of key parameters would change as a subject progresses through their rehabilitation. In order to identify any potential patterns, all TPT data was used in four sub-group regression analyses using the five previously chosen parameters. The standardised coefficients from this larger data set are shown in Figure 5-16.

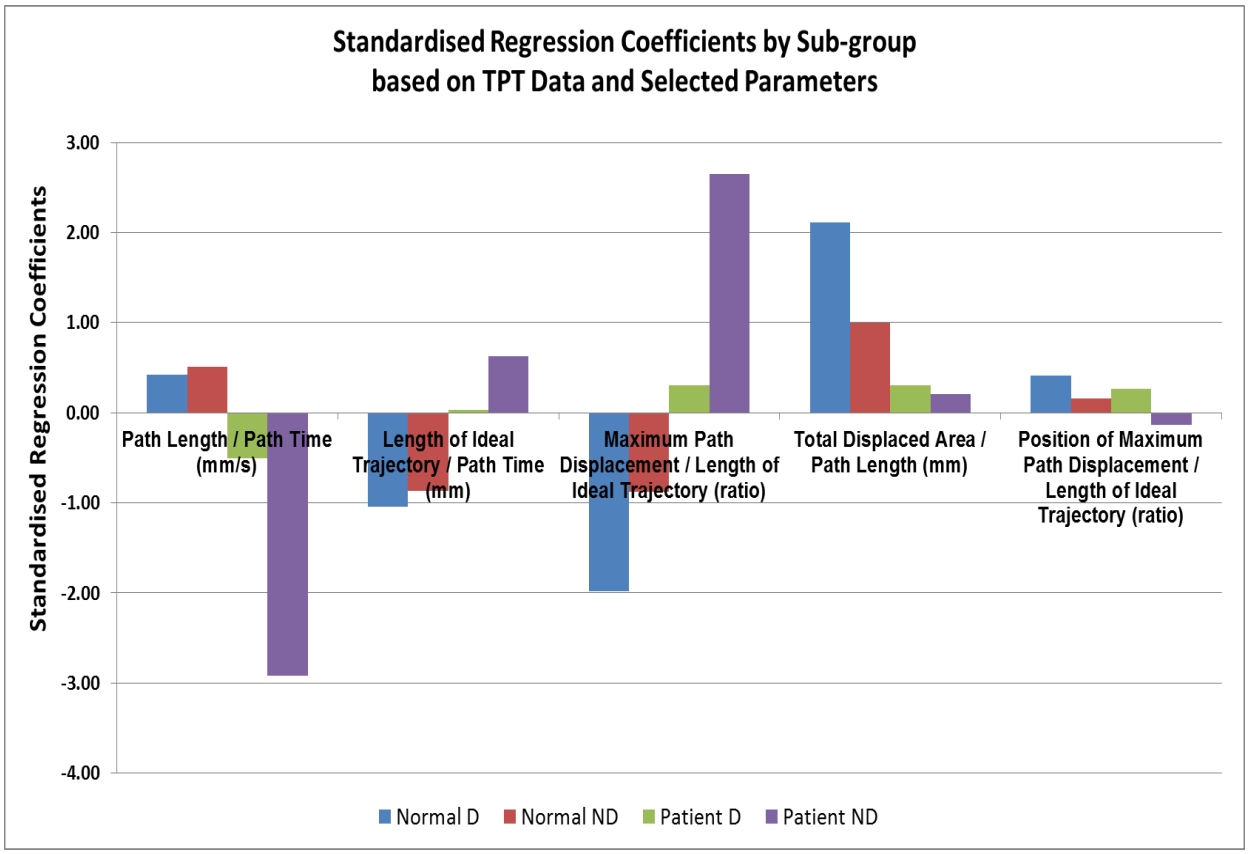


Figure 5-16 Standardised Regression Coefficients by Sub-group

The coefficients indicate some interesting patterns between sub-groups with some being inverted (PL/PT, MPD/LIT) between patient and normal participants. These patterns in the coefficients were adopted to seed the solver for the new metric to enhance stability and help to predict the most suitable weightings for each parameter, as discussed in section 5.5.4.

5.5.3 Developing a New Metric

Development of a new metric was attempted which was not directly regressed from the TPT and parameter data as the SPSS™ models could not be controlled adequately, resulting in variable and sometimes unpredictable results. Instead a logical combination of the five parameters was used and solved for maximum correlation with the TPT data for each sub-

group. This process could be monitored and controlled using user-defined constraints to maintain stability in the results. This was conducted in MS Excel as this was readily available and well-documented solver engine.

It was anticipated that a new metric, a measure of reaching ability, would require different weighting values for the five movement parameters in each subgroup. Ideally, the metric would be clearly differentiated between these four sub-groups although overlaps in the metric would be predictable, as indeed participants' reaching ability between sub-groups was observed to be very variable (see parameter boxplots in appendix 5E).

It was expected that definable regions would be identified and that these regions might actually be subsets of a continuous performance curve with predictable changes in metric coefficients as rehabilitation progressed. Establishing such a metric curve, even in multi-dimensional space, would permit predictable progression to be determined along any suitable rehabilitation continuum.

As noted earlier the normal sub-groups could be differentiated from the patient sub-group regions using PL/PT and TDA/PL as the regression coefficients are inverted, as seen in Figure 5-16. Within a participant group dominant to non-dominant performance was not readily identified from the regression coefficients. However, within the normal sub-groups, large differences in values of MPD/LIT and TDA/PL might be used to identify the sub-groups. Similarly large differences in values of PL/PT and MPD/LIT might be used to identify sub-groups within the patient participants. These differences could be usefully developed as markers to trigger the use of adjacent coefficients to calculate the new metric.

5.5.4 Formulating the New Metric

The new metric was derived from the five parameters described in Figure 5-16. These were standardised for each participant by dividing the parameter by the respective sub-group standard deviation. Each of these sub-groups was allocated a set of weighting factors to maximise the Pearson correlation coefficient with the relevant TPT score. The MA2 score was also monitored for the patient non-dominant parameters but it was not a controlling constraint. Consistent small seed values of 0.1, signed as noted for the standardised regression coefficients, were used as the initial weighting factor to initiate the scaling process so as to not unduly influence the solutions from the solver.

The resulting product of the iterative weighting factors and standardised parameters were summed to predict a value of the metric for each sub-group participant. Correlations were calculated for each of the combinations of the metric and TPT scores assessments until said correlations had been maximised in each subgroup.

Optimisation of the weighting factors was carried out using a solver within MS Excel based upon the generalized reduced gradient (GRG) smooth nonlinear solver engine. The constraints used were simply to maximise the correlations noted above. Correlations were limited to those available in Excel and the parametric function "CORREL" was used consistently for all participants. The solver works on an established algorithm but depending upon the starting values, variable solutions could be obtained. Some superior correlations were possible by using large coefficients but these were not realistic so were limited to being no greater than the maximum absolute value of any standardised parameter. This value was not exceeded by

the solver engine. If this constraint had not been used, very large and unrealistic coefficients would have dominated the actual parameters.

Whilst not used as a constraint, the overall correlation between TPT and metric data for all sub-groups was monitored and this proved to be a significant correlation. Similarly, correlations with the MA2 data (patient non-dominant only) was consistent in that it was negatively signed compared to the TPT correlations. The parameter weighting coefficients and resultant weighted standardised parameters are recorded in Appendix 5H. The parameter weighting coefficient are summarised in Table 5-12 together with the Pearson correlation coefficients from MSExcel™.

Table 5-12 Parameter Coefficients used in new metric

Participants	Weighting Coefficients used in Determining the New Metric					Correlation Coefficient from Excel		
	PL/PT	LIT/PT	MPD/LIT	TDA/PL	PMPD/LIT	TPT	MA2	All TPT
Normal D	0.039	-0.096	-0.183	0.195	0.038	0.874	n/a	0.921
Normal ND	0.079	-0.134	-0.137	0.155	0.025	0.612	n/a	
Patient D	-0.174	0.012	0.103	0.103	0.092	0.666	n/a	
Patient ND	-5.125	1.494	3.489	0.257	-0.191	0.710	-0.649	

5.5.5 Correlations between New Metric and Clinical Scales

The values of the new metric for each sub-group were assessed with SPSS™ for consistency with all preceding analyses. Normality checks on the new metric were satisfied (see appendix 5.H). There are minor differences for some of the correlation coefficients calculated by SPSS™ to those obtained in MSExcel™ and these are recorded in Table 5-13 together with their respective probabilities.

It can be seen from Table 5-13 that there is strong correlation ($r > 0.68$, $p < 0.05$) with the TPT for all sub-groups with the new metric except normal non-dominant which is moderate ($r = 0.666$, $p=0.061$). The correlations between the TPT and all participants taken as a single group is very high ($r >0.9$, $p<0.001$).

Table 5-13 New Metric Correlations with Clinical Scales					
	Pearson Correlation				Linear Fit Line
Correlation	**N**	**r**	**p <**	**Power**	**Residual R^2**
Normal D: Metric to TPT	10	0.87	0.001	0.96	0.764
Normal ND: Metric to TPT	10	0.61	0.061	0.51	0.374
Patient D: Metric to TPT	11	0.67	0.025	0.67	0.444
Patient ND: Metric to TPT	8	0.71	0.049	0.75	0.504
All: Metric to TPT	39	0.92	0.001	1.00	0.848

Notes:
For the purposes of this thesis, correlation coefficients (absolute values) are categorised [183] as follows:
Weak: <= 0.35; Moderate: 0.36 to 0.67; Strong: 0.68 to 0.89; Very high: 0.9 to 1.0.
Not all patient participants completed the TPT with their non-dominant hand.
Power calculation: see section 5.1

The new metric was plotted against the TPT data for each sub-group and the resulting graph is shown in Figure 5-17. The linear line (R^2 = 0.848) and 95% CI boundaries plotted refer to all sub-groups. Similar lines can be plotted for each sub-group individually and the R^2 values are tabulated in Table 5-13.

The data points for the normal (dominant and non-dominant) and patient dominant regions are plotted in Figure 5-18 using an enlarged scale to show the detail which is obscured in Figure 5-17.

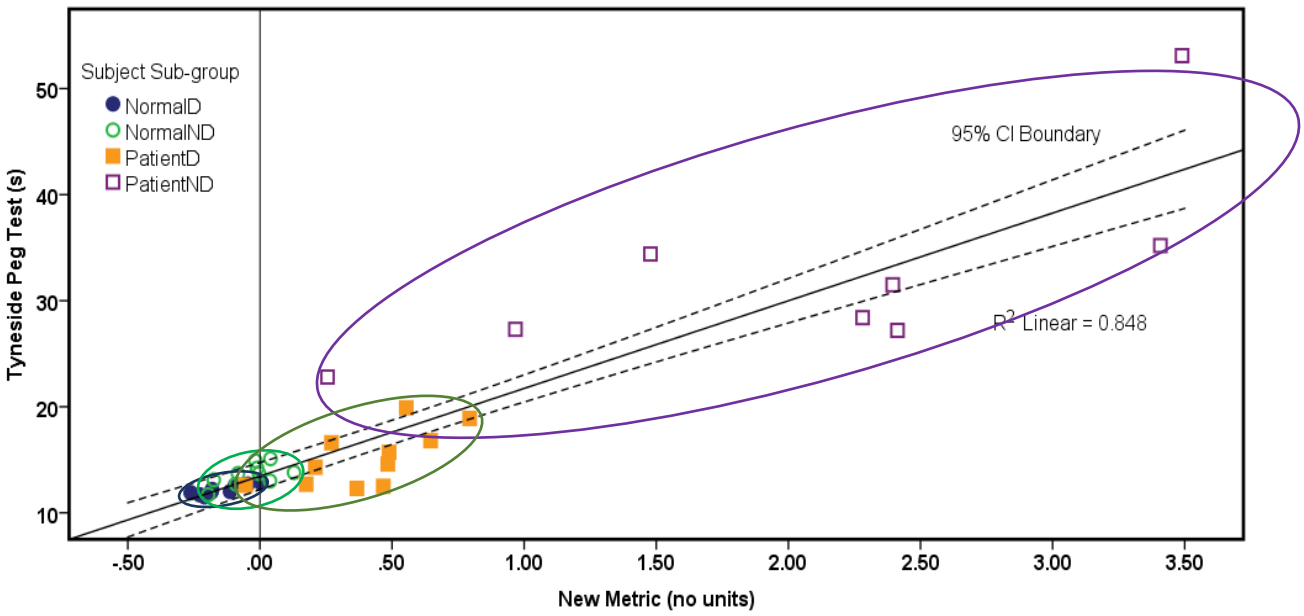


Figure 5-17 New Metric Compared with TPT Scores for each Sub-group

The regions suggested in section 5.5.2 are clearly indicated by the new metric in Figure 5-17 and Figure 5-18 by the clusters of data points and the ellipses that enclose them. These show a distinct separation between patient non-dominant and normal dominant participants although

that between patient dominant and non-dominant is less distinct. Similarly, there is some overlap between patient dominant and non-dominant data points and to a lesser extent between normal non-dominant and patient dominant. This demonstrates that the new metric has the potential to differentiate between the abilities of a wide range of participants.

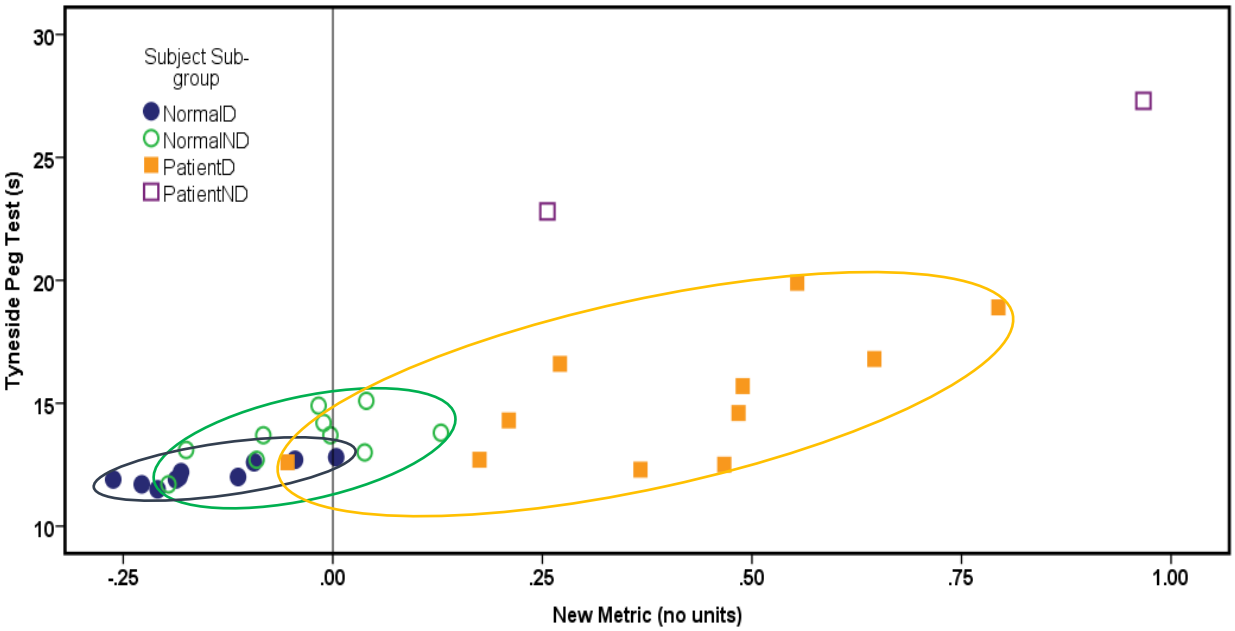


Figure 5-18 New Metric Compared with TPT Scores for each Sub-group (enlarged)

The order of participants presented in Table 5-13 from normal dominant to patient non-dominant indicates increasing potential and observed ability, as identified earlier. There is notable overlap in ability between normal dominant and normal non-dominant as seen in the new metric data points in Figure 5-18.

5.5.6 Dominant Hand and Movement Laterality

The patient group comprised eight left-handed and four right-handed participants, whilst all of the eleven normal participants were right-handed. The patient group does not represent a typical distribution for healthy children. Typically, 10% of participants would be ambidextrous or left-handed [184] which is reflected in the normal group. Therefore, there is a noteworthy disparity in what might be considered natural right-handed participants for whom their CP condition has changed their dominant hand. It is not possible to identify which patient participant might have been "naturally right handed" but is reasonable to assume that the majority might have been.

The twelve parameters used in the first PCA (see section 5.5.1) were reviewed for movement laterality. Some parameters showed notable differences between left-dominant and right-dominant hands for the patient participants (there were no left-dominant normal participants).

5.6 Chapter Summary

A number of movement parameters were identified in the literature and by the author based upon observation of different datasets. It was anticipated that no single movement parameter could be used to describe a state of ability for all of the sub-groups in this trial. This was confirmed by the weak correlations for most individual parameters with the TPT data that was used for comparison with all sub-groups. It is possible that different individual parameters might be more appropriate as measures of ability for different sub-groups but these were not readily identified. Equally, it was not clear when one parameter might be used rather than another as ability changed and so the concept of a new metric was proposed by the author. It was anticipated that such a metric had the potential to be a useful measure of ability if it were based upon a common set of parameters but weighted depending upon anticipated progress within any sub-group.

A procedure for assessing parameters derived from positional and temporal data was developed based upon established statistical and mathematical techniques. The chosen set of parameters for the new metric were selected from initial regression and principal component analyses to identify the most likely combination of parameters to suit all of the sub-groups. The weighting factors for each sub-group were identified by maximising correlations with the data obtained from the clinical assessments.

The new metric correlated well with the TPT clinical scales across all sub-groups with the exception of the normal non-dominant sub-group where only moderate correlation was observed. A distinct pattern of values for the new metric emerged which suggested that an upper limb ability continuum might be definable based on simple reaching tasks. Such data could be used to establish a continuum defined such a metric. The definition of this would be based upon key indicators for each sub-group identified in the chosen parameters which best reflected the abilities with a given sub-group. Such a metric could permit rehabilitation to be quantified by periodic calibration with various clinical scales.

Some unusual features were noted in the parameters and potentially the new metric. Movement Laterality (ML) was noted in some parameters which indicated that patient participants demonstrated a predictable preference or limitation in their reaching tasks, favouring a path to one side of the IT depending upon their dominant hand. This was not noted for normal participants and hence may be used as a marker for progress and in determining the weighting factors used of the new metric.

6 Discussion

This thesis explored the following main hypothesis:

> ***"Simple movement parameters, obtained from varied but repeatable two-dimensional reaching tasks, can be used to establish a state of rehabilitation from which quantifiable measurements can be made to record progress."***

In this chapter the various achievements and limitations of the work summarised in this thesis will be discussed following the pattern of investigation established in section 1.2; namely biological, engineering and human-machine interfacing. These areas are becoming predictably less distinct as technology advances and its acceptance in medical treatments and daily activities becomes ever more commonplace.

The advantages of some technologies that support health and wellbeing are sometimes conspicuous and readily accepted and understood, such as the advances in personal mobility offered by powered wheelchairs and adapted cars. Less obvious to most users are the advances made in diagnostic testing and evaluation that support decisions for treatment and care provision. Most people will have been sent for tests but are largely unaware how these tests work or how the results are interpreted.

The work in this thesis will hopefully support developments that bridge the gap between conspicuous and less-understood health care provisions, allowing users to actively participate in their own assessment and treatment. This is the basis of the ARMaT device investigated and planned as part of this thesis. Such a device will provide an accessible and affordable system that users can work with at their discretion and/or as guided by their health care advisors. The results can be presented as a simple scale and this can be identified in a way that appeals to the user; an increasing value to show improvement or a decreasing value to show reduced errors, for example. The value indicated can be directly related to the proposed components of movement efficiency (ME) and movement accuracy (MA) and these can be illustrated to the users using readily understood concepts. Additionally, the balance of movement might be indicated by a value of movement laterality (ML) but this is requires further investigation and development.

As the beneficiaries of their own efforts users are probably the best advocates and critics of the possibilities offered by advances in technology. If engineers and clinicians are to serve the community then the opinions and experiences of the users should guide what is provided for them. It is anticipated that large-scale deployment of affordable devices can offer valuable feedback from users against which better and more appropriate devices and treatment might be developed. This allows and encourages the direct involvement of users who have the opportunity to understand what the assessment means and how they can influence it.

Technology must continue to advance to meet current and future demands. Hence, the planned development, functionality and engineering specifications for prototype 2 are noted in this chapter and proposed for inclusion in further work.

6.1 Biological

In this section the biological and medical background to the thesis and relevant justification is reviewed based upon a summary of the literature and observations made during the investigations and experimental work undertaken as part of this thesis. Although a direct consideration for biological and medical requirements, the human interface is described in section 6.5.

The concept of a continuum of ability was introduced in chapter 1 and this is reproduced in Figure 6-1 which shows that ability might be represented by a continuous multi-dimensional tube. Here it is shown in three dimensions but many more are probably present. This continuum represents abilities that require cognition, planning and physical execution in real time rather than thought processes alone; being requirements for ADLs, etc. The largest part of the continuum is shown as an irregular tube that is reducing in size (capacity) and is highly variable in section. This thesis addresses the majority of the continuum where full or partial rehabilitation is possible and may benefit from a new ARMaT device.

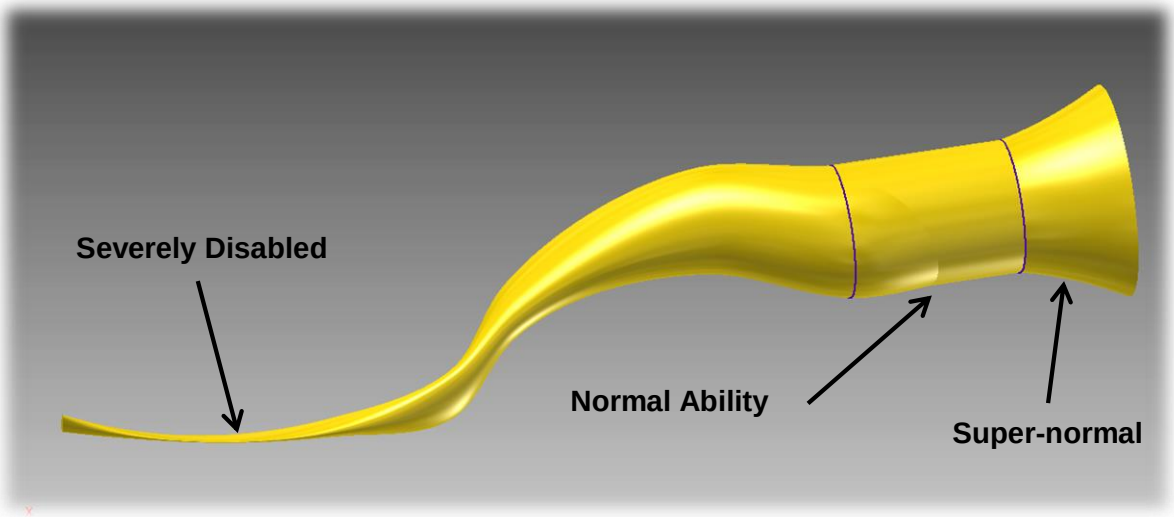


Figure 6-1 Continuum of Ability

As noted in section 1.5, the continuum probably contains multiple strands which help to define it, such as cognitive ability, physical ability and SCS ability. These are shown in Figure 6-2 as three of the potentially large numbers of strands that are needed to define ability and to explain responses to external and internal stimuli. Normal ability is represented by the thinnest part of the strand bundle where the various abilities are refined and aligned. Again, the largest section of Figure 6-2 represents the highly variable nature of abilities in people with conditions that affect one or more ability strands. This section contains diverging strands and interactions between them, some of which may be undesirable. As basic ability diminishes, the strands become more chaotic or may disappear altogether. This thesis did not directly address this extreme but may help inform other work which does.

The work with prototype 1 sought to provide measurements that might usefully predict any state along the continuum of ability, excluding the extremes noted. From section 5.5, it was demonstrated that such a measure has been identified and can be correlated with other established assessments. This is represented in Figure 6-2 which shows a possible arrangement of the two clinical assessments, depicted as multi-dimensional measurement volumes, super-imposed upon the ability strands. There is limited evidence to support the suggested shape and orientation of the measurement volumes. However, the illustration is useful in describing the different results obtained from similar assessments and their potential limitations.

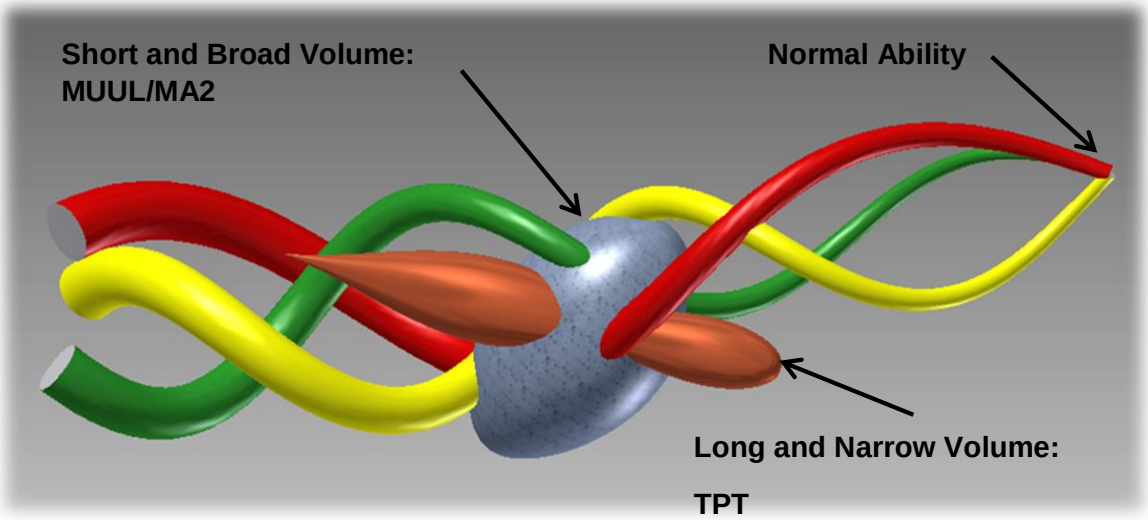


Figure 6-2 Ability Strands and Clinical Scale Measurement Volumes

Given the model proposed in Figure 6-2, it is possible to explain a number of potentially conflicting arguments in the literature and as noted in this thesis. Some scales are useful for particular subjects with specific conditions such as the MUUL/MA2 for children with CP. They might be extended for use with older teenagers with the same condition, or even other similar conditions, but they might not be so reliable outside of the original limits. The variation between the MUUL/MA2 noted in section 5. 1 is an example where the same basic measurements lead to two different but well correlated scales of assessment. They might be depicted by two closely intersecting volumes that are slightly out of alignment with each other. These assessments might be termed "short and broad" as they have limited application but are formed from diverse measurements which probably assess a broad area of the continuum. Conversely, the NHPT (from which the TPT was developed) may be applicable to a wide range of conditions across a very wide age range. However, the simple nature of the task and corresponding single outcome measure may not reflect or record ability in all strands very well. This might be described as a "long and narrow" assessment.

Where assessments are uniform in their application then the shape of the measurement volumes might be regular with few abrupt changes. This is the anticipated shape of a quantifiable assessment based upon known scalable measurements such as the relative parameters introduced in section 3.3. For most assessments, their applicability is unknown and there may well be localised voids or narrow sections in the volumes that indicate significant limitations in measurement potential. These may be permanent voids or faults in

the assessment as some tests are not scalable or are not meaningful if scaled. For example, the MA2 test is unlikely to be expanded to meet demands from adult stroke patients or rehabilitating athletes. Similarly, although the standard NHPT is widely used it has only one measurand, time, and few options to add challenges. Indeed the problems noted with the TPT when using the "small" and "medium" peg challenges might indicate a significant limitation in this type of test. However, the development of the TPT noted in section 5.1 following the clinical trials is an example where an assessment might be expanded and the shape of the volume would change, perhaps becoming longer or broader.

Although it is not possible to confirm the shape and orientation of the new metric it is interesting to suggest a measurement volume for comparison with the two clinical scales used in its development. A possible representation is shown in Figure 6-3. Given its quantifiable and scalable properties it is likely that it is a regular shape, extending over a large portion of the continuum, possibly encompassing most if not all of the strands. It probably intersects with the two clinical scales allowing moderate to strong correlations, at least over portions of their applicable ranges. Whilst regular in section, it is probably not linear but curved to reflect the changing value or relevance of the parameters that form it. This is representative of the variable weighting coefficients introduced in section 5.5. The ends of this measurement volume are as yet undefined as the limits are not known and further testing is required. Finally, the proposed metric is a subset of a more comprehensive metric which might be developed to truly quantify movement ability and perhaps other abilities across the full continuum of ability.

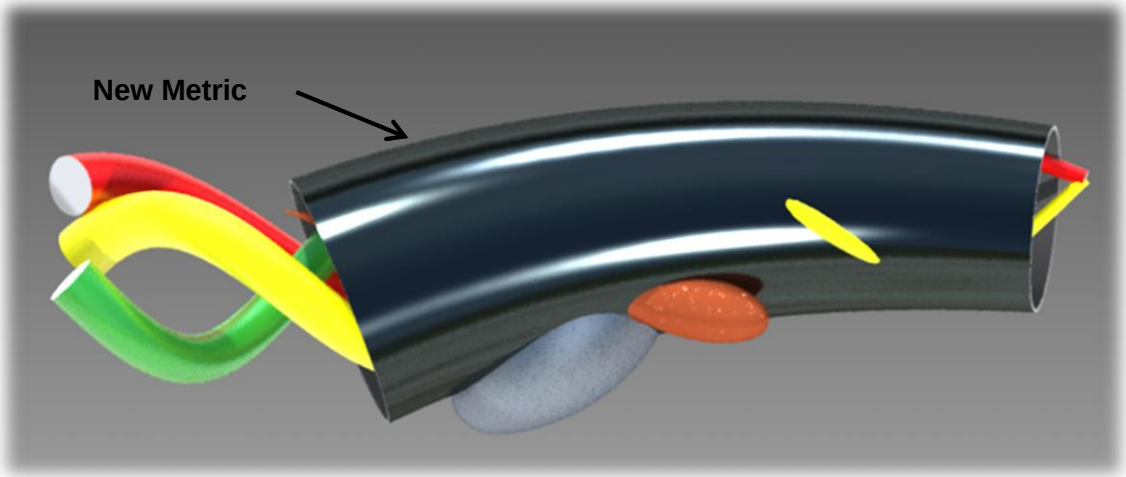


Figure 6-3 New Metric Superimposed on continuum and Clinical Scales

6.1.1 Measuring Rehabilitation

People with physical injuries (and some mental health issues) benefit from clinical treatments, such as setting a broken bone, and then receiving physiotherapy to attempt rehabilitation to a previous state. Similarly, medical treatments are possible following injuries to the brain or nervous system which then require neuro-rehabilitation. The surgery or drug treatments may be different but the common approaches with PT/OT/ST are well-established and essential parts of any health care system. There is significant evidence that varied therapies are beneficial at a functional and neurological level and that the more therapy that is received

over a longer period, the better the short, medium and long-term benefits. Unfortunately, demand often exceeds capacity.

What the best therapy might be is not universally agreed upon and this is due in part to the absence of a coherent and contiguous measure of ability and hence progress in rehabilitation. In order to assess the benefits of any therapy or intervention, various outcome measures have been developed and have become established for assessing different body segments and, more importantly, functional independence where this is possible. Few if any of these outcome measures are transferable between therapies although many are well correlated within similar tasks. However, many measures are qualitative, non-scalable, non-parametric and subject to inter-rater and intra-rater errors.

Before the clinical trial, observations confirmed that this version of the fan-game was relatively simple to complete for most children with normal capabilities. This established valuable benchmarks for the version of the game used for the trial. Although some patient participants demonstrated limited capability with their non-dominant hand they did not demonstrate any notable physical difficulty when using their dominant hand. However, the results suggested a significant difference between the averaged capabilities of normal and patient participants for both hands in this type of table-top reaching task. This suggests that the obvious deficit in the paretic hand is somewhat reflected in the dominant hand. This has been noted in the literature relating to the "unaffected hand" in subjects with CP.

It is possible that the performance of the dominant hand could be used to indicate a reflected measure of performance in the paretic hand. Normal participants also showed differences in ability between dominant and non-dominant hands which were notable for some the parameters used in the new metric, see section 5.5.2.

6.1.2 Results from Prototype 1

Section 5.5 presented the results obtained from prototype 1 and considered correlations with the two contemporaneous clinical scales used. A reproducible method (see section 5.1) was used to identify a suitable set of parameters common to all sub-groups. A new measurand, determined by a structured combination of the suitable movement parameters was also examined and the validity of this as a new metric is discussed.

Early tests on normal participants with the concept B device demonstrated that the fan game was almost trivial for children with "normal" capabilities. This identified valuable floor and ceiling limits for the version of the game used with prototype 1 and for the patient and normal participants assessed. The results for normal participants typically indicate small differences for most parameters when comparing dominant and non-dominant hands. These differences are very small compared to those noted between normal dominant and patient non-dominant sub-groups.

6.1.3 Potential Metrics

Some movement parameters could be readily identified from the graphs in appendix 5E as being potential measures of performance, with clear differences in individual capability and between normal and patient participants. As well as differences there were similarities in some parameters between all participants. In particular the averaged position of maximum path displacement (PMPD) from the ideal trajectory (IT) divided by the length of the ideal

trajectory (LIT) is reasonably consistent between all participants (being within 55 to 65% of the LIT) and between dominant and non-dominant hands. Similarly, data for maximum path displacement (MPD - a measure of MA) divided by the path length (PL - a measure of ME) show that there is less distinction between the groups. However, when MPD is divided by LIT to normalise the paths notable differences between the sub-groups become obvious.

The data suggest that the PMPD might well be similar between participants, perhaps suggesting a common ballistic movement, but that participant capability can be differentiated by using the most suitable parameter; in this case MPD/LIT rather than MPD/PL. It is also possible that any notable deviation from a common value of PMPD could indicate a significant issue with either the data gathered or the participant's performance. This might make such parameters useful markers of performance transitions or alerts to data errors rather than measures of ability.

Some parameters such as PT and MPD/LIT are perhaps predictably much smaller for normal participants, indicating markedly more efficient and accurate movements than for patient participants. Other parameters such as PL/PT and TDA/PL are still significantly better for normal participants.

There is a significant difference in ability between hands which is typically worse for non-dominant hand but highly variable for the patient participants. It is possible that patient participants were particularly careful to follow a direct line to the target and achieved better accuracy (MA) at the expense of slower times (ME). Normal participants also spent more time with their non-dominant hand than their dominant hand compared with patient participants and their performance in all parameters (compared with patient dominant) was improved for this investment.

6.1.4 Correlations between Clinical Scales

The correlations between the clinical scales used were summarised in section 5.5 and suggest that there is moderate correlation between the total scores for MUUL/MA2 and TPT time results. The subscales within MUUL/MA2 were also examined and these showed moderate to strong correlations for the TPT when moving from left- to-right (l-r) for the Dominant hand and for right-to-left (r-l) for the non-dominant hand. Given the limited data set (ND: N=8) no conclusions can be drawn as to the reliability of these results. However, as noted later in section 6.2 there is an effect of handedness or ML in the parameters extracted from the fan game which may be relevant in any new metric and in assessing correlations with clinical scales.

The results indicate that the clinical scores were useful reflections of similar abilities although they probably represent very different measurement volumes on the continuum of ability. They may also have been orthogonal to each other and simply overlapping in the region assessed for these participants. It is useful to note that the value of parametric correlations with both scales was used to determine the new metric in the solver engine described in section 5.5 and that this process resulted in rapid and stable optimisation.

In their paper Basu *et al.* [185] compared 33 patient participants and 66 controls (some of whom are represented in this thesis) using the TPT. The clinical team concluded that:

"The "unaffected" hand in children with hemiplegia is less dextrous than the dominant hand of controls. Therapy to improve function of the more-affected hand should be designed to achieve optimal outcomes bilaterally".

This confirms the observations noted in the literature on the ability of the "unaffected hand" and also identified in the movement parameters explored in this thesis, and reflected by the new metric.

6.1.5 Movement Laterality (ML)

It is known that bilateral effects can be used to train a paretic arm as an aid to rehabilitation. Given the results noted for the TPT and the fan-game, supportive training and potential assessment might be possible using the dominant hand. Johnson *et al.* [25] recorded data from normal participants to provide a baseline for their diagnostic tool based upon a force-feedback steering wheel. They noted (p18) that *"neurologically unimpaired subjects, with intact volitional control"* exhibited no significant differences during testing indicating that they would do equally well with either or both arms. This provides support to the observed data and this concept requires further study and larger data sets which will be discussed in chapter 7. Lum *et al.* [14] noted that the assisted mode in their MIME system provided access to users with all levels of impairment and that progress was rapid in the first two months and was sustained compared with a control group. However, they note that some measures were not significantly different between the groups after six months as the control group continued to improve. They advocate (p958) the use of bimanual training with their MIME system as it *"provides both visual and proprioceptive feedback of a properly moving limb in phase with the attempted movement".*

Investigations into healthy participants using simple bi-manual exercises have been carried out by Marteniuk *et al.* [88] who noted a significant difference between movement and reaction times for dissimilar but simultaneous tasks such as reaching distance and stylus mass compared with similar simultaneous tasks. Most notable is that bi-manual tasks were slower than one-handed tasks indicating greater sensorimotor processing and cross-linking for bi-manual tasks. This is in contrast to that reported by Johnson *et al.* [25] although the task was notably different (reaching compared with steering). They also identified significant differences in handedness where the dominant hand was generally more accurate (MA) and/or faster (ME). It is therefore reasonable to anticipate some differences and similarities in each hand and for each task and this might be reviewed in future trials.

Within the patient group there were eight left-handed and four right-handed participants, whilst all eleven normal participants were right-handed. The patient group does not represent a typical distribution for healthy children where 10% of participants might be expected to be ambidextrous or left-handed. Hand dominance is generally dictated by the hemiplegia observed in the participant and assessed by the therapist.

The dominance of left or right side path movement was noted from the additional parameters ALHS and ARHS bounded by the path either side of the IT. The area to the left or right of the IT was more notable than displacement (MPD). Movements were predominantly left sided for right-handed participants within both participant groups, and more significant for patient participants. The magnitude of path side dominance decreased as the trajectory angle increased. For left handed patient participants, this pattern was reversed indicating path

dominance to the right of the IT. The variation with angle was not as marked as for right handed patient participants.

Normal participants (all right handed) demonstrated some path side dominance and variation with trajectory angle but this was generally less significant than that for patient participants. It is worth noting that the smaller trajectory angles were to the right of the home base and the larger ones to the left. Hence, when using their right hand a participant would move to the right of their centre-line to follow trajectories with an angle less than 90° and to the left for angles greater than 90°. The pattern of movement would be reversed when using their left hand. Given the previous discussion on bi-lateral movements, some mirrored behaviour about the centre-line would be predictable.

The ML effect is interesting and suggests some relationship between natural handedness and that imposed by the ABI. The sample is too small to confirm any particular relationship but this might be studied in future research. The clinical team did note a relationship between the "unaffected hand" and the degree of impairment noted in a wider sample of patient participants using the TPT. No mention of natural handedness was made.

It is known [87] [186] that bilateral effects can be used to train a paretic arm as an aid to rehabilitation. Given the above results it might be possible to use the non-paretic hand as a rapid assessment indicator, especially if training were designed to be bilateral. To develop this concept requires further study and larger data sets.

All participants played sufficient games to establish their best performance at their stage of rehabilitation or development. The notable differences in performance between normal and patient participants confirm that patient participants generally have a lower starting ability. They may well be able to attain the benchmarks achieved by normal participants and this would be a good indicator of progress that would be simple to measure. There is some limited evidence to suggest that following therapy and repeat tests with prototype 1, patient participants can demonstrate an improvement that is measurable on the proposed parameters and correlates with the TPT data. This area of work is inconclusive as there were too few participants but it could be explored in further clinical assessments and longitudinal studies.

Although other challenges were not examined with the any of the participants using prototype 1, it is reasoned from the work to date that normal subjects would achieve a level of proficiency which might be considered normal for their group and provide similar benchmark values to those obtained for the fan-game. The application of new challenges to patient participants would be possible and will be explored in section 7.2.

6.2 A New Metric of Ability

It can be seen from the results in section 5.5 that a new metric can be determined based upon parameters derived from simple positional and temporal measurements using reproducible selection process described in section 5.1. A pattern of parameter importance was identified using PCA techniques although these could not be directly mapped to the proposed movement quality indicators ME, MA and ML.

Following the successful completion of the trials with prototype 1 and the identification of a potential new metric, a paper by Cameirão *et al.* [9] showed a successful trial of their rehabilitation gaming system (RGS) together with a composite metric that they used to determine the next level of gameplay. This approach provides a clear and rapid indicator of progress which is very valuable to users and their carers and is consistent with the author's intention of providing a new ARMaT device and metric. As with the new metric the RGS scoring is bespoke to the game played but correlates well with clinical scores. Being based upon the kinematic parameters established by Cameirão *et al.,* the RGS scores should be quantifiable and scalable. The RGS is a more sophisticated system than that proposed in this thesis and may well be more limited in application as it requires volitional control in three dimensions rather than for the planar desktop activities that helped to determine the new metric. Presumably it would be possible to reconfigure the RGS to planar motions that do not require support of the paretic arm.

Colombo *et al.* [89] used simplified metrics based upon their "robot score" which was a measure of the proportion of volitional movements over prescribed segments of predetermined paths. They also noted that the mean velocity of movements increased notably with progress and that positional accuracy (distance from ideal trajectory) correlated well with their "*robot score*". Although the robot score is specific to the ART device that they developed, it correlated well with established clinical scales. The positional accuracy that Colombo *et al.* note might be considered analogous to the author's parameter of PMPD, a more simple measure of accuracy used in the new metric.

More recently Krebs *et al.* [32] noted that robotic measurements can identify "*biomarkers of motor recovery*" in longitudinal studies of stroke patients. All of these indicators correlated well with a number of clinical scales and this suggests that such markers may be found in other bespoke measurements and used to identify key changes or the progress of rehabilitation. In formulating the new metric in this thesis, the author proposes that markers are used to indicate when parameter weighting factors might be changed to reflect progress, see section 5.5. It is interesting that such markers appear to be developing within various research strands and it is possible that these may hold key information to help identify and define the continuum of ability.

There are considerable similarities between the approaches used by the author and established researchers and this supports the methodology of determining potential parameters and a new metric from a combination of parameters. The distinctive feature of the proposed ARMaT device and subsequent reported research is that the developments described in this thesis do not seek to reproduce the results of other researcher but to look openly at further potential. As an example, the increase in mean velocity noted by Colombo *et al.* is identified as a potential parameter but is not a prescribed measurement. Similarly, the greater complexity required to

determine volitional movements by Colombo *et al.* is not available in the proposed ARMaT device and hence cannot be used as a parameter. The planned affordability requirements noted in section 3.1 precluded the functionality intended by researchers using ART devices.

Further work and larger data sets are required but the potential to develop and apply a rapid and reliable, affordable, continuous metric of rehabilitation has been demonstrated. The new metric might be developed to track progress from an initial state of measurable ability to near-normal performance. Whilst this thesis has addressed upper limb movements, the methodology used could be extended to other body segments.

Further refinements in measurements and metrics are indicated and might include normalising laterality parameters to determine the effects of this observed behaviour on treatments. This might inform existing treatments or influence the importance of targeted therapy to address notable laterality.

Further parameters might be determined using additional measurements which might extend the measurement volumes proposed for continuum of ability noted in Figure 6-1. It is anticipated that assessments from near paralysis to normal functioning and further, into enhanced performance training, should be possible for two and three dimensional activities.

6.3 Engineering

The over-riding objective for the work on the ARMaT devices was to provide an accessible system that would benefit the widest range of users be they patients, carers, clinicians or researchers. It might seem unlikely that one device could achieve this but the rationale is simple. If the device benefits the patients then the carers can enjoy this with them and progress for both in functional independence and/or enjoyment of life is a reasonable expectation. Where the patients are seen to benefit, and this can be measured objectively, understanding of existing treatments improves and these can be more effectively monitored and prescribed by clinicians. Further, new treatments and interventions can be assessed more readily and safely allowing clinicians greater scope and freedom to support patients and carers. Finally, the significant datasets that would be possible from a mass deployment of accessible device would support research into conditions that are currently limited by small sample groups and poor availability of longitudinal studies.

The engineering imperative was to design and test a new measurement system that was useful, accessible, affordable, believable and scalable. This was planned using a predictable design development process that constantly referred to these objectives to ensure that proposed solutions were valuable and would not be so sophisticated that they might never become used, however valuable they might be.

The following sections address the design and implementation of prototype 1 and provide a critique of the systems in preparation for developing more advanced and reliable prototypes. Additional information is provided in the appendices noted below.

Although all of the data presented in chapter 5 was obtained using the very simple PC-based system described in section 4.4, there were significant concerns about the reliability of any systems that used the Windows OS as the basis for measurement. When considering the ultimate requirements of interfacing with further sensors or a potential haptic device, the unresolved data clustering and other minor game-play issues were very likely to prove impossible to resolve if more functionality were to be added. In addition, the visual interface was rather basic and any attempt to make this more complex or interesting resulted in further data capture and VRE synchronisation issues. These issues and potential solutions are documented in Appendix 6A.

Although the software limitations were overcome for the trials with prototype 1 this was not a workable solution for full implementation. A number of software variations were trialled following the clinical assessments to reduce these effects but with only limited benefit. A complete redesign of the software was required and this is described later.

In addition to the reasons presented in section 3.3, there are further practical arguments for using relative parameters which became obvious from the testing phase. There was some inconsistency within the game set-ups, participant activity (even if properly directed) and limitations with the measuring software. The following observations made during set-up and testing reinforced the recommendation for using relative rather than absolute parameters when selecting suitable measurands:

- Calibration issues between individual games (home position, etc,) and participants (ability and level of attention) were variable and could not be controlled effectively without affecting game play.
- Trajectory angles and lengths are not equal and hence averaged absolute measures were not meaningful, although this could be overcome with additional analysis
- Variations in physical and visual placement could not be standardised across all participants although seating position and table access were made as similar as possible for all participants

Considering the many limitations on using absolute measurements, there is no proposal for benchmarking absolute parameters such as PT. These may be quite large even for normal subjects if the reaching task is significant or the exercise prolonged. However, there is value in understanding the possible limits of all chosen parameters so that software and hardware can be developed to accommodate anticipated usage. For these reasons suggested ranges are proposed for the chosen five parameters and these are noted in Table 6-1.

Table 6-1 Suggested Measurement Ranges for Potential Parameters

Parameters used in Analysis	Anticipated Range
PT (s)	600 (5 minutes)
PL / PT (mm/s)	0-2000
LIT / PT (mm/s)	0-2000
MPD / LIT (ratio)	0.0 - 2.0
TDA / PL (mm)	0 to 100
PMPD / LIT (ratio)	0 to 2

Prototype 1 comprised a number of mechanical components, both bought-in and bespoke manufactured items, standard fixings, bespoke electronics and bespoke software, together with the PC base unit and display screen. The cost of many of these items is readily identified from suppliers. Manufactured items are more difficult to assess for costs but an approximate value has been calculated based upon an initial delivery volume of 1000 units. The target maximum manufactured cost of £1000 presented in section 3.1 developed from published household income data and represents a value similar to that spent annually by many families on leisure and cultural activities.

Prototype 1 was designed to minimise costs and hence make this ARMaT device available to the widest range of users whether they purchase it themselves or receive it on loan from health care providers or charities. The costings were reasonable and the target was not exceeded. Hence this prototype could be delivered for the market sector identified in much of Europe and most developed countries.

6.4 Principal Developments from Prototype 1

The work carried out on prototype 1 with patient and normal participants identified a number of important changes that would be required in the next prototype if the full value of further trials was to be realised. As a result of a detailed technical review with the software engineer, it was concluded that a new system should be designed, based upon new positional sensors and utilising a bespoke PIC-based data management system. The Windows OS would be replaced with a Unix OS and all unnecessary software, processes and potential interrupts would be removed from the OS. This would leave a bare PC to cope with the considerable data transfer, processing and storage requirements as well as the graphical interface.

The following sections address the key elements explaining the origin of the requirement, potential solutions and the design that was developed for prototype 2. More detailed documentation for the development of prototype 2 is contained in the Appendices.

For the reasons noted in appendix 6A control and data capture would be carried out using a custom PIC-based interfacing board. This permits the relatively high speed data capture algorithms to be separated from the OS which had proved to be a concern in prototype 1. The PIC could also store sufficient data so as not to interrupt game play and enable data transfer at the end of a session.

The basic format and performance of prototype 2 will be based upon the performance specification introduced in section 4.1. This is essentially the same as for prototype 1 but with developments for the inclusion of velocity and acceleration measurements. These are summarised in appendix 6B.

The results from the parameters developed with prototype 1 identified the potential for additional parameters to yield more consistent data and/or additional information. The range of parameters or combinations available from the XY positional data were exhausted with prototype 1. Further parameters will require additional sensors and enhanced data capture capability and will be selected within the context of an affordable application and deployment which was a guiding principle for this research.

The most obvious choice for potentially valuable parameters would be related to acceleration. Due to rapid advances in MEMS, accelerometers are a low-cost sensor technology that may be readily incorporated within small spaces. They provide valuable and cost-effective XYZ and rotational measurements of acceleration within the ranges required. They are reliable, robust and readily interfaced with data acquisition units and controllers.

Although accelerations in X and Y are required for the 2-D parameters discussed so far, the addition of the Z-axis is a valuable parameter although not strictly required at this stage. A suitable board containing a tri-axis chip and circuitry is available that could be mounted within the skate to prevent inadvertent interference by the user and to centre the sensors' origin over that of the skate's movement.

6.5 Human Interface

Without a significant need, little progress is made in engineering and medical science. Arguably, the medical need is always present as the human body changes to adapt to age and environment. The opportunity to support human needs, and desires, is significant and offers great opportunities to help many people around the world. It can also offer significant commercial advantages in meeting these needs and desires and this requires careful consideration if the right balance of value and profit are to be achieved.

In this section the human interface with ARMaT devices is reviewed, particularly in the context of what has been learned during the development of prototype 1 and what might be taken forward to best effect in supporting rehabilitation.

For most of the patient participants in the early observation sessions, gripping, handling and guiding a standard PC mouse with their paretic hand was almost impossible. Similar problems were noted for the TPT where patients were asked to use their non-dominant hand. As a result this original data was not widely reported by the research team who devised them.

The original concept for the game included the introduction of virtual challenges; the most favoured being a form of constant rotational offset, added without the knowledge of the participant. For example, in order to follow a trajectory at an angle of 30° to the horizontal on the screen, the participant needed to push the mouse at an angle of 60° on the table. Many patient participants compensated for this by rotating the mouse the required additional 30° of correction and then executed a 30° degree path. This unexpected behaviour caused a major review of the experimental approach with concept B. It was interesting that the participants who did this, both patient and normal, actually managed to adapt their behaviour in real time, often hitting the target as well as those who did not introduce an early rotational correction. It is notable that whilst the proposed challenge was a fixed rotation angle many participants were introducing, and compensating for, highly variable rotational and lateral movements caused by the uncontrolled rotation of the mouse.

As noted in section 2.5 the effect of the test environment and the health and/or attitude of the subjects can have a significant effect on the reliability of any results obtained. Although a number of simple tests (such as eyesight, blood pressure, body temperature, room temperature, lighting levels, etc,) might have been conducted very easily, none of these were observed for the clinical assessments that preceded the use of prototype 1. Indeed, the literature rarely makes mention of any subject or environment assessment prior to testing. The few examples noted are limited to determining a basic visual acuity test or requirement for spectacles.

It was not possible to request any additional tests on the participants and hence no baseline data exists for assessing the effect of environment or participant condition beyond known hemiplegia. Such conditions may well be a significant factor in the results and should be investigated or eliminated in future assessments.

6.6 Chapter Summary

This chapter has discussed the work carried out to develop and deliver an ARMaT device which provided the results presented in chapter 5. The main areas of discussion are based upon the biological aspects, engineering design and human interfaces that were established in section 1.2. These areas are mutually dependent and whilst presented separately they cannot be considered in isolation.

Based upon the selected parameters, a new metric was proposed such that significant simultaneous parametric correlations with the clinical scale were obtained. This method can be extended to any suitable clinical scale, making the process a potentially powerful and independent predictor of rehabilitation progress.

The continuum of ability was revisited from section 1.5 in the context of the results obtained and proposed metrics. The new metric probably represents a "regular, long and broad" assessment as it is formed from diverse but related measurements that can be performed by a wide range of subjects with varied conditions. It is potentially sensitive to small changes and can be expanded upon with additional tasks for the same basic measurements. The breadth of the metric can be expanded by introducing new challenges and refinement improved by adding further measurements such as accelerations, etc. It is the start of a set of quantifiable metrics which are inter-related and derive from simple and understandable measurements.

The results obtained with prototype 1 were discussed in detail to identify how the main aims and objectives of the thesis were addressed, what has been achieved and what remains to be investigated. The limitations of the engineering designs, assessment procedures and experimental works were explored and solutions identified for consideration in future work to overcome limitations and take advantage of the opportunities that the results have provided.

7 Conclusions and Further Work

This chapter draws together the main conclusions from the work with prototype 1 and supporting research and development. It looks forward to further developments and future research opportunities. It considers the use of ARMaT concepts, both as described in the current application to children with CP and to wider potential applications. The continuum of ability shown in Figure 7-1 has been proposed to assist in explaining the relevance and application of a new metric.

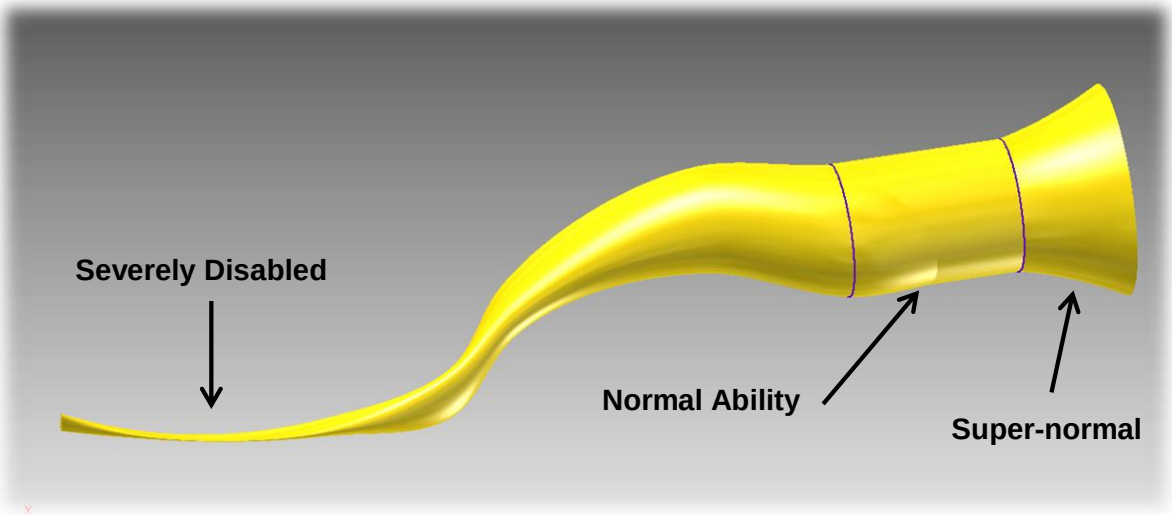


Figure 7-1 Continuum of Ability

7.1 Conclusions

This thesis explored the following hypothesis:

> ***"Simple movement parameters, obtained from varied but repeatable two-dimensional reaching tasks, can be used to establish a state of rehabilitation from which quantifiable measurements can be made to record progress."***

The author sought to support the essential work of clinicians, therapists, carers and the patients themselves who require rehabilitation following injury, be it acute or chronic. The main objective was to provide all interested parties with an accessible, simple and believable "ruler" to measure rehabilitation progress and/or the effect of a therapy for the upper limb.

The absence of any comprehensive and extendable measurement system for rehabilitation led the author to develop the concept of a measureable continuum of ability, as introduced in section 1.5 and presented in Figure 7-1. Within this continuum lie the many ability strands that permit basic and extraordinary skills to be developed. More importantly it can also identify deficits or limitations in ability and hence might be used to support rehabilitation efforts. This concept allows for the many clinical assessment scales to be superimposed upon the various strands and explains how they might be correlated locally despite measuring varied and/or isolated aspects of ability. This approach led to the formation of the above hypothesis and successful attempts to define a more comprehensive and contiguous measure of ability based upon simple movement parameters.

The aims and objectives needed to examine this hypothesis were simply stated but complex in their delivery. Despite a number of significant technical and organisational challenges a simple device was developed that has the potential to capture movement parameters that describe movement ability in the upper limb. Using a structured methodology, these parameters can be combined to form a believable new metric that correlates well with an existing clinical scale and is expected to correlate with further measures of rehabilitation of the upper limb and potentially other body segments. The system has demonstrated that significant potential exists in simple measurements to provide dynamic assessment of rehabilitation.

The two assessments (MUUL/MA2 and TPT) used in the clinical study required a significant amount of setting up, notable time to conduct the assessment and further post-processing of results. In particular the MUUL/MA2 setup requires multi-point video capture and the space to contain this elaborate and expensive system, although the tasks themselves can be contained on a table top. Typical installation costs for the MUUL/MA2 equipment are unknown but estimated to be in excess of £6000 based upon current technology. The original equipment would have greatly exceeded this sum. The TPT is significantly more compact and easier to set up than the MUUL/MA2 although the original test has now been developed to address limitations in the earlier form reported in this thesis. The system reported in this thesis was a low-cost peg-board and PC with interfaces which probably cost a similar amount to prototype 1 (approximately £700).

For the MUUL/MA2 system a typical assessment required 20-30 minutes to conduct with 30 minutes post processing. The TPT typically required 10-20 minutes to conduct and 5-10 mins to process although this latter stage could have been automated. The MUUL/MA2

assessments require continuous involvement of a trained therapist. It is also notable that the therapist needed to physically intervene for many participants during both clinical tests and that considerable verbal encouragement was provided. In contrast, all participants managed to complete the fan-game using prototype 1 successfully with minimal verbal encouragement and no physical intervention. Assessment time for the five fan games undertaken by each participant was typically ten minutes and post-processing (once automated for the new metric) would take less than 1 minute. Prototype 1 could therefore, be considered more reliable, more accessible and more achievable than the other assessments.

The primary objective of this project was to develop an affordable and accessible ruler to assist subjects, their carer's, therapists and clinicians in assessing rehabilitation progress. It needed to be simple and quick to administer, non-invasive and readily deployed to a mass user group. The final cost of such a system might be a significant obstacle to mass deployment and ownership. Given the projected commercial production cost of under £1000, it was anticipated that many users could afford to purchase or hire such a system from the health care providers or suitable charitable organisations. A more sophisticated and robust variant could be used within clinical settings.

Although prototype 1 could be developed for commercial use, the limitations noted in section 6.4, and the potential for additional parameters and metrics, indicate that a new prototype would be an advantage and this is discussed in section 7.2.

With the development of the new metric proposed in this thesis, states of ability can be identified for children with CP such that rehabilitation can be reliably measured for the upper limb; only a small part of the continuum of ability introduced by the author in Figure 7-1. This is the start for developing a metric curve for the upper limb such that any traceable metric can be used to extend beyond the new metric to describe larger volumes of the continuum of ability. Although initially applied to the upper limb, further metric curves could be developed for any body segment, or potentially a specific skill such as writing. These curves would be able to measure and respond to the changes in ability and could be adapted and developed to suit future assessments based upon measurable movement as and when they become available.

7.2 Further Work

The original research was inspired by the potential of haptic devices and rehabilitation robotics to support patient recovery from acute and chronic conditions that affect their daily lives. These areas of research are growing in complexity and application with some systems now in regular use for therapy or training. It is still a rapidly developing area of science and engineering but the potential for improving quality of life is substantial. The work with prototype 1 to date supports the wider application of ART by offering an accessible ARMaT "ruler" to measure state and progress of rehabilitation. There is still much to be done in developing the proposed new metric to meet existing and foreseeable needs.

As noted in section 3.6 a further device, prototype 2, was anticipated to develop the potential of prototype 1. This was planned within this thesis and is reported here to show the design decisions and their justification. Many detail design developments will be required to meet safety guidelines for a clinical prototype and this is anticipated in the simple design and open-source nature of the methodology noted in section 3.1. Some of the planned developments were introduced in section 6.4 and more detailed plans are contained in appendix 6B.

Clinical participants are often difficult to identify and to maintain for longitudinal studies. Hence, advanced data capture was planned to gather and identify further potential parameters, and develop more metrics. To this end a redesigned unit was developed based upon draw-wire positional sensors and low-cost accelerometers, introduced in section 3.2. Data capture was based on a dedicated PIC interface to permit expansion of inputs and outputs, including small format tri-axis accelerometers and enhanced stability of data streams via a USB interface. The VRE was maintained on the PC but using Unix-based software and hardware to eliminate Windows OS interrupts and associated random data corruptions.

The design is already in progress and an early unit has been built for preliminary testing. Assessments indicate notable stability improvements in the data streams to and from the VRE and robustness of the skate and playing surface.

The draw-wire sensors provide a spring field that maintains the orientation of the skate as well as providing more accurate and reliable positional measurements. Whilst only two sensors are required for positional measurement, the use of four draw-wires balances the spring field exerted on the skate and also allows for enhanced positional measurement.

The fan-game used in prototype 1 was maintained in the new VRE and is part of a suite of new games under development. These were designed to assess improving cognitive and physical skills as rehabilitation progresses by providing a range of challenges and more elaborate tasks. Although none of the participants found the fan-game very challenging, simpler games can also be developed to allow participants with lower abilities to benefit from the system.

A new handle and skate design were developed to house and support the new sensors and to ensure that all users could disengage from the device in case of urgent need or welfare concerns.

The VRE used in prototype 2 expanded upon and varied significantly from that in prototype 1. The earlier audio-visual environments were considered rather limited and not-sufficiently specific to the user or patient. A software configuration which provided more variable

environments was designed which allowed appropriate images to be displayed to suit children, adults, males and females. All environments occupied the same screen size and images were selected to be non-intrusive and offering limited distraction to the user. Audio signals were minimised as were rapidly moving graphics (other than the cursor) so that the user could concentrate on the task.

Although the device is not an active haptic solution, additional challenges are possible using added weights. The basic skate weighs 0.4 kg and this can be changed easily by the addition of simple weights within the skate. This can be achieved readily by the therapist with limited disruption. The added mass not only affects the inertia of the skate but also the friction between the skate and the playing surface due to the increased load on the five ball feet.

7.3 Chapter Summary

The results of this thesis indicate that a rapid and affordable assessment system can provide a reliable and meaningful measure of ability in the upper limb for children with Cerebral Palsy. A new metric is proposed that correlates well with two established clinical assessments and this is indicated in Figure 7-2.

The methodology and measurements presented demonstrate the potential for simultaneous assessment and therapy and indicate that ARMaT is a reality. The simple and traceable nature of the work provides opportunities to extend the measurement of ability and hence rehabilitation beyond the initial application to many other subjects and conditions.

The potential for ARMaT is considerable and ranges from home-based exercises advised by a therapist through to computer-based exercises built around games or required PT/OT activities. Immediate feedback and support for users and carers is possible and this will inform rehabilitation progress and advance further therapies and interventions.

More elaborate and challenging games and environments can provide useful extensions to the work carried out so far and the methodology developed can be readily extended to develop further metrics. This work is currently under investigation and includes additional measurements to identify further parameters for prototype 2 that should support and expand upon the new metric developed with prototype 1.

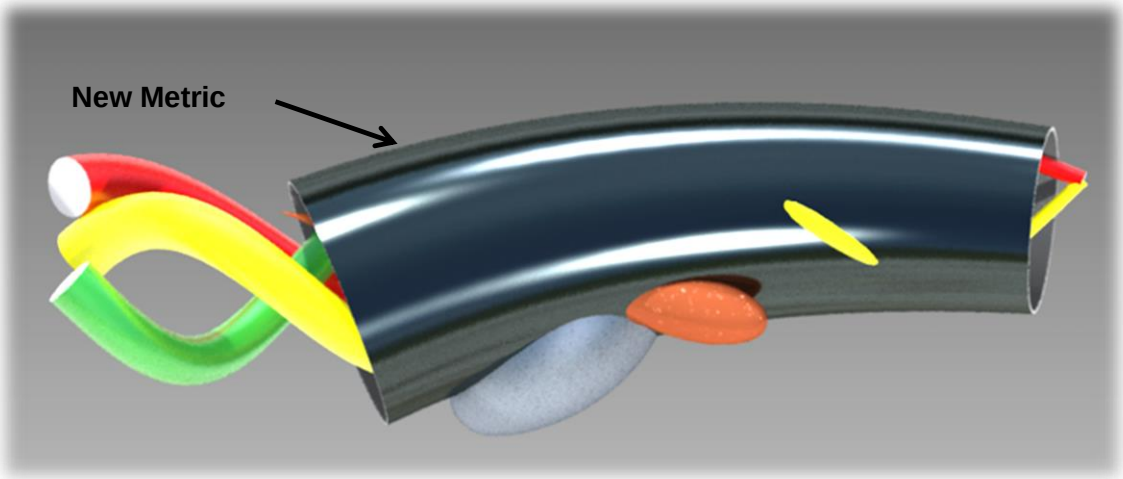


Figure 7-2 New Metric Superimposed on Continuum and Clinical Scales

8 Appendices

The following appendices are titled following the chapters that they support. For example appendix 3A is referenced to chapter 3.

Section 8.1: Appendix 3A - Measurement Terminology

Section 8.2: Appendix 3B - Measurement Errors

Section 8.3: Appendix 4A - Calibration Data for Prototype 1

Section 8.4: Appendix 5A - Standard Instructions to Therapist

Section 8.5: Appendix 5B - Standard Instructions to Participants

Section 8.6: Appendix 5C - Participants and Clinical Assessment Data

Section 8.7: Appendix 5D - Boxplots of Tyneside Peg Test Data

Section 8.8: Appendix 5E - Boxplots of Movement Parameters

Section 8.9: Appendix 5F - Principal Component Analysis Data

Section 8.10: Appendix 5G - Initial Regression Analysis

Section 8.11: Appendix 5H - Basis of New Metric

Section 8.12: Appendix 6A - Technical Limitations with Prototype 1

Section 8.13: Appendix 6B - Development of Prototype 2

8.1 Appendix 3A - Measurement Terminology

Whatever measurement is required, the quality of that measurement must be determined in advance in order that the correct sensor and processing system is selected and then operated within its declared range. All measurement devices and systems contain inherent errors of reading, conversion, operation, transmission or manufacture. In addition, there are errors introduced by environmental factors, human intervention and random errors with no identifiable source or control strategy. By specifying the most appropriate quality measures for the device and system such errors can be accounted for or ignored. The following is a simplification of standard metrology terminology so that realistic and reliable sensor and data-processing decisions can be made. A more detailed description is provided in [174].

The following sections propose typical related concepts in biological measurements to identify similarities with engineering measurements and to clarify common misconceptions encountered in the course of this research.

Range
The range of a device is the limit of its reliable and repeatable measurement. A 1 m steel rule cannot measure more than 1 m without a deliberate movement that can itself introduce errors. A steel ruler is generally a linear measuring device with similar accuracy within its range. There are devices that become less accurate at the extremes of their range; typically thermometers and pressure/force sensors and accelerometers are in this category. This non-linearity can be accommodated if calibration data is available and corrections can be made manually or within software, using lookup tables or equations which approximate the non-linearity. Commercial sensors have stated ranges and typical linearity curves and can be calibrated to improve accuracy. Selection within the anticipated range is always desirable as operating within a narrow band of a wide range will reduce accuracy and precision, particularly with digitised signals, as noted in appendix 3B.

Accuracy
This defines the closeness of a measurement to a known standard. A simple steel ruler may be manufactured to produce marks at 1 mm intervals with 0.2 mm accuracy and might cost less than £3. Hence a measurement of 26 mm could be 25.8 or 26.2 mm if measured consistently to the centre of each mark. The reader can introduce their own error from lack of care (missing the centre mark), parallax error (angle of view) or bending the ruler! The nett effect could be another 0.5 mm of inaccuracy. It is important to note that the cumulative accuracy of the ruler is typically always +/- 0.2 mm so that a measurement of 998 mm would be 997.8 to 998.2 mm whereas human error may increase with the scale of the measurement.

Resolution
In the example of a ruler, the resolution is 1 mm and accuracy is +/- 0.2 mm. There are no marks between each 1 mm mark so this is the finest resolution possible with such a simple device. In contrast a Vernier calliper rule may be manufactured to a high accuracy, say +/- 0.02 mm, but the basic resolution is the same. The enhanced resolution is achieved by the Vernier scale which sub-divides each 1 mm interval by ten units offering a (simplistic) overall accuracy of +/- 0.02. The cost of such a device may be £20-50. When converting measurements to digital form for use within control systems or VREs, the resolution of the digitising hardware and software can be a significant limit on resolution and indirectly on

accuracy and repeatability. This is discussed in appendix 3B where data processing is considered in more detail.

Precision

Strictly speaking, precision is a measure of repeatability and may be described by the standard deviation of a sequence of measurements against a known value. Many digital devices appear to offer valuable measurements due to the large number of decimal places that might be displayed. Typically, the number displayed is generated by the digital division of a higher value such a voltage reading of 100 V but displayed on a LCD screen with a maximum range of 5 V. The precision of measurement might be 0.001 V but the accuracy might only be +/- 0.1 V in a low-cost instrument. Similarly, temperature measurements which convert small signals to voltages can display with a resolution of 0.1 °C and may offer precision of 1 °C but at the extreme range might fail to meet an accuracy of +/- 5 °C.

Time Measurements

Accurate time measurement is relatively straightforward with modern digital devices. Indeed the time-stamp is fundamental to all other data measurement whether as a record of events or sequence of tasks or for further use in deriving velocity or duration. Typical accuracies are very high as on-chip or on-board crystals are very stable and their frequency is derived digitally from many millions of counts per second. Typically a crystal will oscillate at 4-20 MHz and will be divided to hundreds of counts per second (0.01 s) without significant degradation of integrity as errors and missed counts are divided out – a missed count in 10,000,000 oscillations is less than 0.00001% error in a time-stamp of 0.01 s. Using high speed devices is commonplace now and is required to derive many measurement parameters.

Positional Measurements

The most obvious measurement for upper limb rehabilitation is position and these are routinely taken in most ARMaT system. Moving from position 1 to position 2 to pick up a pen requires a displacement of X and/or Y and/or Z mm. How this measurement is achieved is discussed later but, for basic Cartesian displacement, reliable and suitably accurate measurements in X and Y (2-D) or X, Y and Z (3-D) are required. Polar coordinates may be more appropriate in rotational devices and conversion between these two reference frames is simple and predictable.

Velocity Measurements

The speed and quality of movement can be related to the velocity with which the participant moves at various stages of a typical reaching movement [69, 89, 148]. Such measurements can provide insights into the mechanisms affected by various conditions, particularly as rehabilitation progresses. These measurements are not always made routinely as direct velocity measurement is difficult and the sensors required can be large or intrusive. Typically, the velocity or speed is derived from displacement and time data, both of which can be readily recorded, as has already been noted. There are however, significant issues in using the derived data.

Acceleration Measurements

Low-cost accelerometers based on micro electro-mechanical systems (MEMS) technology have allowed unobtrusive tri-axis measurements to be made within small devices. These are now ubiquitous sensors in nearly all modern mobile phones, and other hand-held games and gadgets. Unlike velocity sensors, accelerometers use predictable reactions to small masses and

hence very rapid accelerations can be transmitted as analogue or digital signals following conversion and basic processing. Calibration is reliable and straight-forward for simple movements. However, rapidly changing movements result in spikes of acceleration which are not observed in real movements. As with velocity sensors, smoothing and filtering can make the signal look believable but, integrity is inevitably lost. For relatively slow movements, such as gameplay or mobile phone gadgets, or one-shot sensors such as airbag sensors, this is not considered problematic. Unfortunately, many devices are based upon "gameplay algorithms" which distort both input and output data as real movement is not the object of the measurement, that being secondary to smoothness of gameplay.

Force Measurements

Force can be measured directly using relatively low-cost sensors as the likely forces involved in typical table top tasks are small. The accuracy of the force vector is important if meaningful parameters are to be extracted. This would require that forces are measured as close as possible to the user's point of contact and that the direction was constrained to be aligned with the positional measurements. Alternatively, for a given dynamic arrangement, acceleration data could be interpreted against known masses/inertias to calculate approximate forces exerted in the direction of the accelerations recorded. Whilst acceleration sensors are small and relatively inexpensive and simple force calculations with known mass are straightforward, assessing the dynamics of an ARMaT device and a human body is not. It is unlikely that such derived force measurements would be truly meaningful as the behaviour of the device could not be isolated from that of the participant without creating an artificial environment. However, the user's reaction to a change in mass and the resultant friction would provide a potential challenge which might be reflected in more reliable positional measurements.

8.2 Appendix 3B - Measurement Errors

This appendix contains a detailed assessment of the types of measurements and errors that can be expected in digitised signals and can be referenced when considering the design limitations noted in the chapters 3 and 4.

Analogue -to-Digital Conversion Errors
A voltage from a potentiometer in a displacement sensor of + 5.0 V can be readily sampled by a typical 12-bit ADC. This sampling rate results in 2^{12} = 4096 steps to provide a fine digital representation of the analogue distance measured. With no other pre-processing of the data, this provides a discretisation step of 5.0 V/4096 = 1.2 mV/step. Taking a typical reaching movement of 500 mm, there is an inherent limit of resolution of 500 mm/4096 = 0.12 mm. This resolution is notably smaller than that typically required for rehabilitation. Accuracy is a function of the sensor and this can be factored into assessments of reliability of sensor signals. Precision of conversion is typically very good.

Accelerometers may be sampled by an on-board ADC with 12-bit resolution. For a typical range of +/- 3 g (1 g = 9.81 m/s) a final resolution of 6.0/4096 = 0.0014 g or 0.01 m/s^2. Again the resolution would be better than that required for successful measurement. However, data from accelerometers is very noisy with significant low amplitude and low frequency noise superimposed upon the required signal. A low pass (15 Hz) filter [76] is often used to reduce the noise and remove unrelated spurious signals and this should be applied to all axes. Cross-talk between the channels is known to be an issue with packaged tri-axis devices so this must be assessed based upon manufacturers data sheets and declared tolerances. Given the accuracy and resolution of even low-cost devices, it is unlikely that errors will be so large as to limit their use.

For relative and absolute displacement sensors such as rotary encoders used with a PC mouse or on rotating shafts, the step is constant and the individual count is not corrupted by any conversion. Provided the step can be related to actual mouse movement, step counts are a very precise and reliable measurement and require no pre-processing.

Computational Errors in Processing Numerical Data
It was noted in section 3.4 that the extraction of derivatives from numerical positional data to provide velocity and/or acceleration data may not be reliable, particularly where complex motion paths and digital sampling are present. This is an area which concerned the author greatly throughout the course of this project as any new metric can only be as reliable as the data upon which it is based. If the data sets have been modified or corrupted by unexplained and uncontrolled mathematical processes then the metric would be less quantifiable, potentially unreliable and hence less valuable.

Some data sets are published with little reference to the integrity of the resulting derivatives. Methodologies such as filtering and smoothing were occasionally noted but the effect that these techniques have on the raw data were never discussed or illustrated. Initially, it appeared that acceptable standards had been established for such analysis or that a “house-approach” had been validated within research groups. It quickly became apparent that the former was unlikely and this caused concern over the latter assumption. Even established motion capture software was noted as being somewhat less than rigorous in the treatment of start and end points, which are critical in assessing discrete reaching tasks.

The computational overhead required for processing data is significant and approximations are often made to present the data in a more manageable format. This is probably more than acceptable for film production and gross movement analysis but not for a refined and scalable "ruler" upon which rehabilitation therapy and possibly medication may rely.

Noise and Discretization

Earlier, the resolution of the ADC for data from a typical reaching movement was shown to be 0.12 mm, which is perfectly acceptable to meet typical rehabilitation measurement accuracy of 0.5 - 1.0 mm. However, when subtracting such data from itself, such as in calculating finite differences for simple numerical differentiation, errors are introduced due to discretisation (position is reduced to a number of discrete steps rather than a continuous function) and rounding errors in the mathematical engines. When these errors are divided by small time steps, they become amplified with predictable and unpredictable results.

Predictable errors can be simulated using rounding errors to mimic the effects of an ADC. Such a simulation is reproduced for a simple and predictable sine wave motion shown in Figure 8-1. These errors are shown in Figure 8-2.

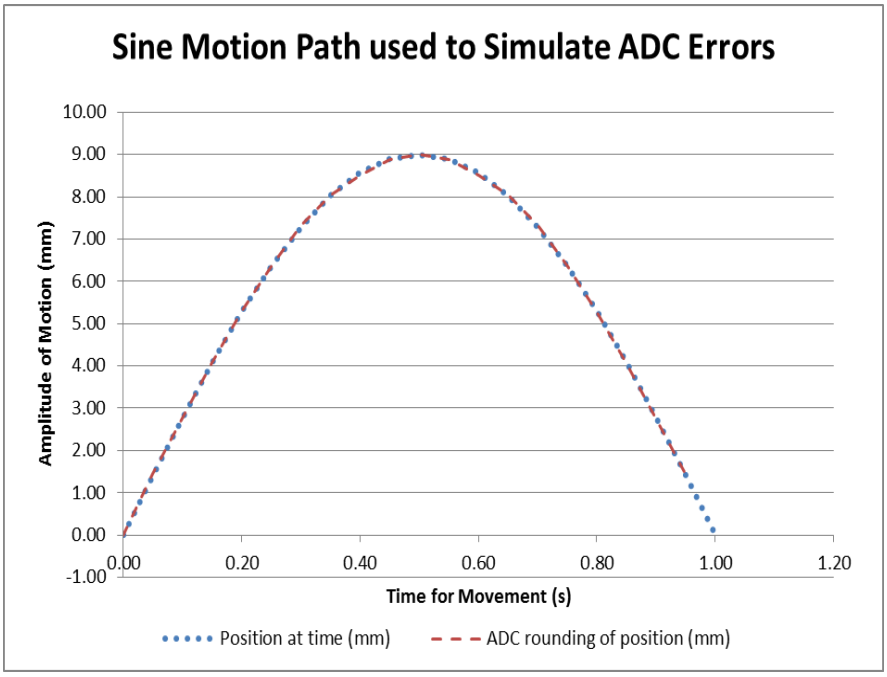


Figure 8-1 Path Used in Sample Simulations

Data for the sine wave with amplitude between 12 and 75 times the ADC resolution was simulated as being sampled with a 12 bit ADC of 0.12 mm resolution. This results in a maximum of 2% error in positional accuracy which might be considered acceptable, being less than 1 mm in error. However, when the difference in position for each time step (delta position and delta ADC in Figure 8-2) is divided by the time step to approximate the velocity this results in a maximum, and highly variable, error of minus 9 to plus 11%. When the amplitude is reduced to between 9 and 60 times the ADC resolution the velocity errors are minus 35 to plus 19%.

Simulated Data of Errors Introduced by ADC Sampling								
Timestep (s)	0.05	0.05	ADC resolution (mm)	0.12				
Time	Position at time (mm)	Delta position (mm)	Velocity from change in position (mm/s)	ADC rounding of position (mm)	Delta ADC (mm)	Velocity from change in ADC	% change position (position - ADC)	% change velocity (Position - ADC)
0.000	0.000			0.000				
0.050	1.408	1.408	28.158	1.440	1.440	28.800	2%	-2%
0.100	2.781	1.373	27.465	2.760	1.320	26.400	-1%	4%
0.150	4.086	1.305	26.095	4.080	1.320	26.400	0%	-1%
0.200	5.290	1.204	24.083	5.280	1.200	24.000	0%	0%
0.250	6.364	1.074	21.478	6.360	1.080	21.600	0%	-1%
0.300	7.281	0.917	18.344	7.320	0.960	19.200	1%	-5%
0.350	8.019	0.738	14.758	8.040	0.720	14.400	0%	2%
0.400	8.560	0.540	10.809	8.520	0.480	9.600	0%	11%
0.450	8.889	0.330	6.594	8.880	0.360	7.200	0%	-9%
0.500	9.000	0.111	2.216	9.000	0.120	2.400	0%	-8%
0.550	8.889	-0.111	-2.216	8.880	-0.120	-2.400	0%	-8%
0.600	8.560	-0.330	-6.594	8.520	-0.360	-7.200	0%	-9%
0.650	8.019	-0.540	-10.809	8.040	-0.480	-9.600	0%	11%
0.700	7.281	-0.738	-14.758	7.320	-0.720	-14.400	1%	2%
0.750	6.364	-0.917	-18.344	6.360	-0.960	-19.200	0%	-5%
0.800	5.290	-1.074	-21.478	5.280	-1.080	-21.600	0%	-1%
0.850	4.086	-1.204	-24.083	4.080	-1.200	-24.000	0%	0%
0.900	2.781	-1.305	-26.095	2.760	-1.320	-26.400	-1%	-1%
0.950	1.408	-1.373	-27.465	1.440	-1.320	-26.400	2%	4%
1.000	-6.891E-15	-1.408	-28.158					

Figure 8-2 Sample Data to Show Effect of Discretization in ADC

The rapid degradation and unpredictable errors with decreasing signal size compared to ADC resolution are shown in Figure 8-3. It is clear that as the signal amplitude approaches the ADC resolution, the resulting errors render the velocity data useless. The most significant errors occur at points of inflection or crossover and this can be seen in the simulated data above where the velocity approaches zero or the path crosses an axis. This is a predictable result and one which is usually cited as a reason for fitting polynomial curves to experimental data. For classical forms, this approach may provide reasonable approximations which can then be reliably differentiated using calculus. However, real movements contain subtleties that curve-fitting may disguise or destroy and more sophisticated numerical methods are required [177]. Similarly, real movements contain very complex paths which no classical form can reliably reproduce over the full length of a movement. Hence, a method is required to extract derivatives from numerical data reliably and simply so that errors can be identified and accounted for in subsequent analysis.

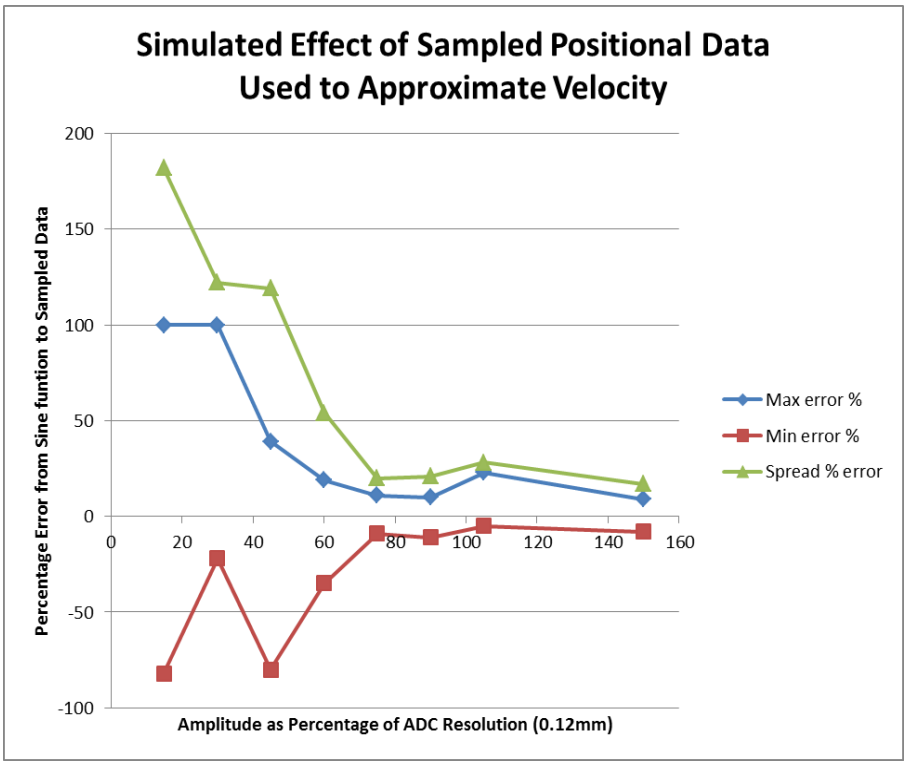


Figure 8-3 Degradation of Integrity of a Sampled Positional Signal

8.3 Appendix 4A - Calibration Data for Prototype 1

The accuracy of prototype 1 was assessed in the laboratory prior to and following use with participants to confirm that the required data was representative of the movements undertaken by the participants. The required positional accuracy was taken from section 4.1 as 1.0 mm and that for time measurements as 0.1 seconds.

Positional checks were carried out by locating target marks on the playing surface at 0, 90, 180 and 270 degrees from the horizontal. These ordinal points were located on two fixed radii (100 mm and 200 mm) around the known centre of the playing surface which formed the centre for all measurements. The skate was positioned within a circle (diameter 175 mm) drawn on the playing surface at this centre before each measurement was taken. Each of the eight calibration marks were used as the centres for a circle (diameter 175 mm) which allowed the skate to be accurately positioned over the centres of the calibration points. Initiating a calibration cycle zeroed the position and time data. Positional accuracy at the starting position and each radius was within 0.5mm as measured using a standard 300mm steel rule (Rabone Chesterman No411DR) with 0.5 mm increments.

The skate was moved to each of the eight calibration points from the centre point taking care to avoid under or over-shooting by aligning the rim of the diameter 175 mm skate with each of the calibration circles. After each point was reached, it was returned to the centre circle. As these calibration checks were not timed, this exercise could be carried out repeatedly. After each of the eight points had been reached, the data file was downloaded and the calculated measurements for the end-points noted. After conversion (see section 4.4.2) all calculated measurements were within 1mm of the 100 mm and 200 mm radii. This calibration process was repeated five times with similar results. The system was deemed to demonstrate the required accuracy.

Calibration against the screens used was more problematic but was achieved using the fan-game settings in the version of the software deployed for the tests. The point of target acquisition was marked on the screens using a sharp dry-wipe marker point for each of the five standard trajectories. This was repeated five times. Following each fan-game the points were measured on the screen from the home base centre using the steel rule. All positions were consistent with the data downloaded and these are noted in Table 5-4. The differences between the planned and actual trajectory lengths and angles was as a result of minor errors within the hard-coded software which did not permit adjustment. As all measurements were taken with the same version of the software and none of the angles or lengths were critical, this was accepted.

Timing checks were carried out separately and did not require movement of the skate. The game was initiated to coincide with the PC clock (this being deemed to be sufficiently accurate, being based on the PC master timer) passing to a new minute. The game was allowed to run for between three and five minutes. The game was stopped at the point of the clock passing a new minute using a key-press. The data files were downloaded and the recorded data (after conversion) for each duration was confirmed as being within 0.1 seconds of the planned three to five minute duration. Any deviation from this was considered to be related to delays/anticipation when hitting the start or stop key-press to initiate or stop the game.

Table 8-1 Target Trajectories Relative to Home Base					
Planned and Measured Target Details	**1**	**2**	**3**	**4**	**5**
Planned Length of IT (mm) from Software	180	120	180	120	180
Measured Length of IT (mm) from screen	177	118	177	118	177
Planned Angle of IT from horizontal from software (degrees)	30	60	90	120	150
Calculated Angle of IT from horizontal (degrees)	27	58	90	122	153

8.4 Appendix 5A - Standard Instructions to Therapist

Therapist Notes for Testing Session	
1	Before the session starts, give each participant a simple Player ID. Initials are preferred. Introduce the game. It is important that consistent instructions are given. Show and explain the “Rules of the Game” to each participant.
2	Complete the players' details, (initials, date of birth, known medical conditions, dominant hand used) together with any notable issues such as cognitive ability, limited arm movement or notable injuries. Start with the dominant hand first.
3	Set up the first game with the five preloaded configurations (game 1…game 5). For each new player load the games and insert their Player ID and hand used.
4	Sit the player directly in front of the board with the skate central to their body. Confirm that they can reach to the edges of the playing area. Play one game as a short familiarisation exercise. Do not record the results for this.
5	When one game is completed, select the MSExcel button. Within Excel save the file with the player ID as the file name. Repeat for all five games. Confirm how many games were played and any notable issues before the next game starts
6	Repeat steps 3 to 5 using the non-dominant hand.
7	Confirm how many games were played by that player and any notable issues before the next player starts.

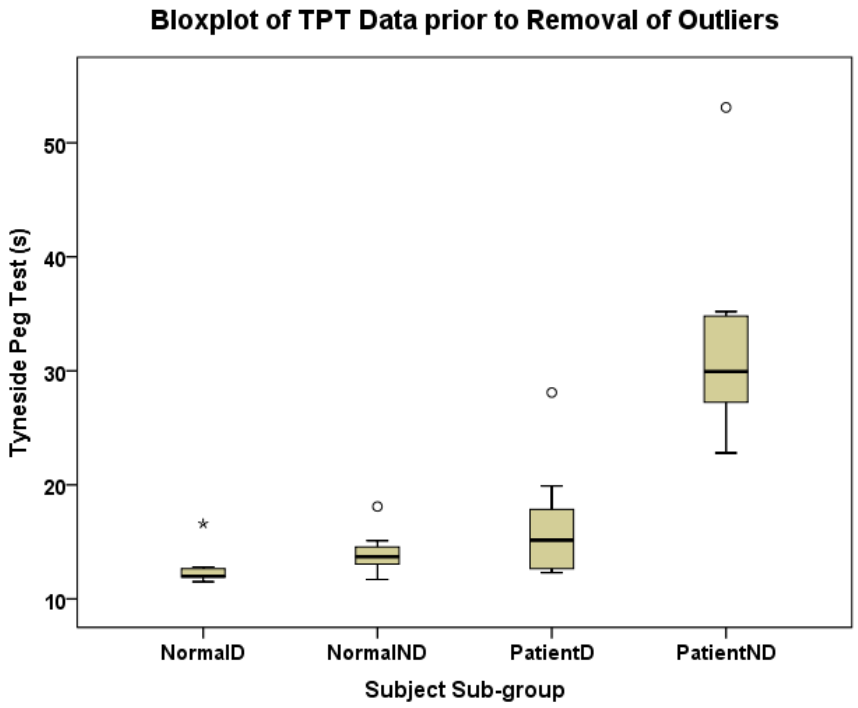
8.5 Appendix 5B - Standard Instructions to Participants

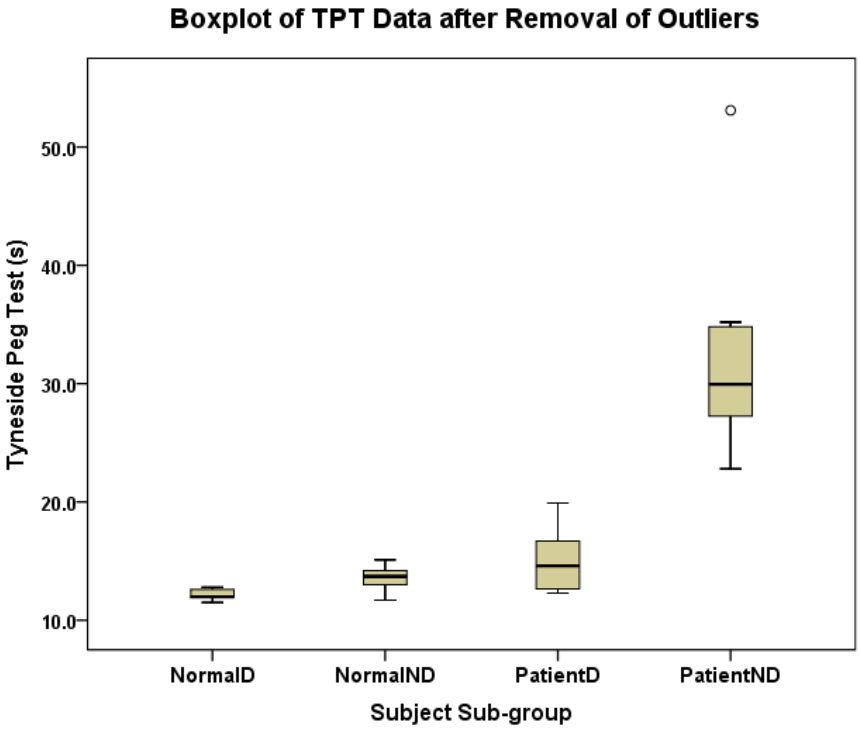
Rules of the Game
Thank you for taking part in this Game. We hope that it will be fun!
You will each have a practise game to understand how the game works.
You start at the **Green Home** and try to hit the **Red Targets** with the **Blue Cursor**
Use the **Blue Cursor** to hit the **Red Targets** accurately without going past them. Some are harder to hit than others!
When you hit a **Red Target**, go back to the **Green Home** to show the next target.
Next time try with your other hand!

8.6 Appendix 5C - Participants and Clinical Assessment Data

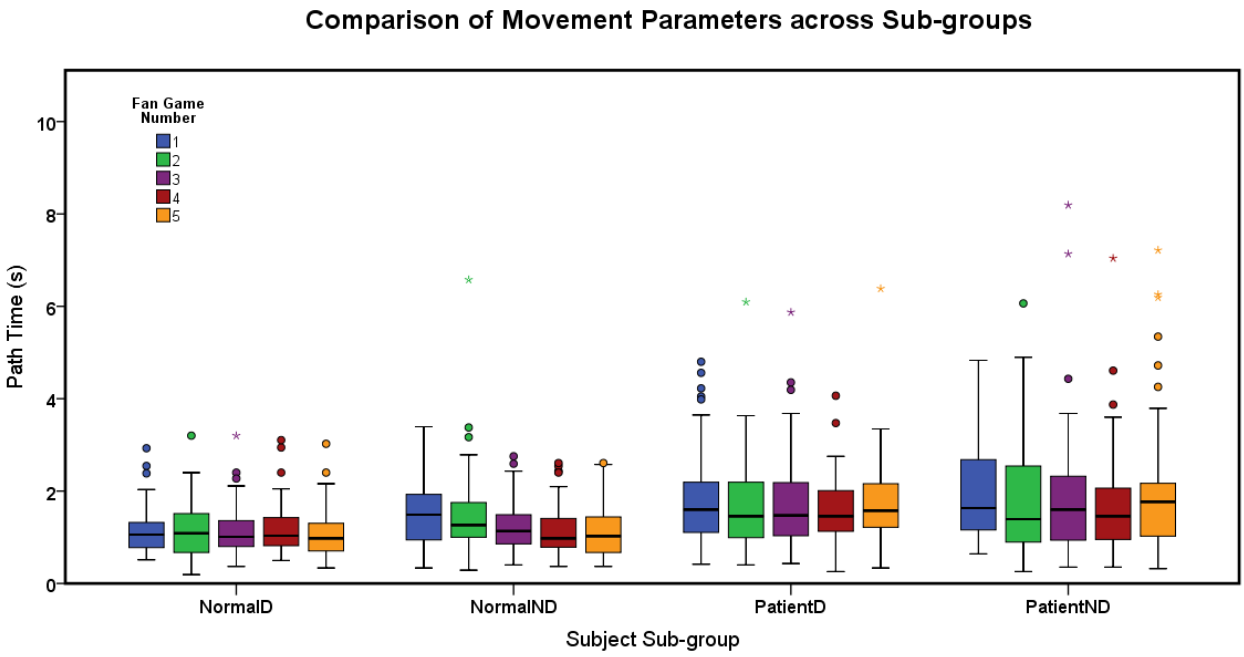
	Ident	Dom hand	Notable issues	Gender	Age at test (yrs)	Hands tested	Fan-games	Tyneside Peg Tests					Melbourne Assessments										
								Dominant		Non-dominant			MUUL						MA2				
								Large L to R	Large R to L	Large L to R	Large R to L	Average Dominant	Average Non-dominant	MUUL total % Score	Melbourne No Fluency	Melbourne Function	Melbourne Fluency	Melbourne ROM	MAT2 Total % Score	ROM	Fluency	Dexterity	Accuracy
Patient Subjects	A	L	R Hemiplegia	F	7.7	both	10	18.0	19.9	n/a	n/a	18.9	n/a	61	62	63	51	57	62	67	52	56	67
	B	R	L Hemiplegia	F	7.7	both	10	13.7	11.4	30.4	39.9	12.6	35.2	61	63	68	53	50	58	48	48	50	48
	C	R	L Hemiplegia	M	7.7	both	10	14.9	13.8	22.8	40.2	14.3	31.5	70	72	80	63	54	67	56	57	69	56
	D	L	R Hemiplegia	F	7.7	both	8	11.9	13.5	27.3	27.3	12.7	27.3	90	88	95	97	86	88	81	95	75	81
	E	L	R Hemiplegia	M	7.7	both	10	19.9	n/a	n/a	n/a	19.9	n/a	24	24	22	27	29	21	19	33	0	19
	F	L	R Hemiplegia	M	7.7	both	10	15.5	16.0	n/a	n/a	15.7	n/a	37	37	40	40	29	34	26	38	13	52
	G	L	R Hemiplegia	F	7.7	both	10	11.3	13.3	n/a	53.1	12.3	53.1	66	69	66	63	64	66	63	62	47	84
	H	L	R Hemiplegia	F	7.7	both	10	17.2	16.4	28.4	n/a	16.8	28.4	91	91	95	90	82	90	89	86	81	89
	J	R	L Hemiplegia	M	7.7	both	10	15.5	13.6	24.3	21.3	14.6	22.8	85	84	93	87	64	82	67	86	75	67
	K	L	R Hemiplegia	M	7.7	both	10	12.1	12.9	26.4	28.0	12.5	27.2	59	58	68	60	36	57	41	57	63	41
	L	R	L Hemiplegia	M	7.7	both	10	16.5	16.7	36.4	32.5	16.6	34.4	72	74	80	67	61	72	63	62	81	63
	M	L	R Hemiplegia	M	7.7	both	10	28.7	27.6	n/a	n/a	28.1	n/a	24	22	24	30	21	24	19	33	6	19
Normal Subjects	AA	R	none	F	7.7	both	10	13.3	10.7	12.6	14.9	12.0	13.8										
	AB	R	none	F	7.7	both	10	13.9	9.9	12.5	14.9	11.9	13.7										
	AC	R	none	F	7.7	both	10	12.6	11.7	13.5	16.4	12.2	14.9										
	AD	R	none	F	7.7	both	10	12.0	12.0	12.8	12.6	12.0	12.7										
	AE	R	none	F	7.7	both	10	11.7	11.7	13.0	14.4	11.7	13.7										
	AF	R	none	F	7.7	both	10	12.1	13.6	16.4	13.7	12.8	15.1										
	AG	R	none	M	7.7	both	10	12.4	10.7	10.8	12.7	11.5	11.7										
	AH	R	none	M	7.7	both	10	16.7	16.4	17.0	19.2	16.6	18.1										
	AI	R	none	M	7.7	both	10	12.9	10.9	12.0	14.1	11.9	13.0										
	AJ	R	none	M	7.7	both	9	11.7	13.7	14.1	14.3	12.7	14.2										
	AK	R	none	M	7.7	both	10	14.1	11.2	12.5	13.6	12.6	13.1										

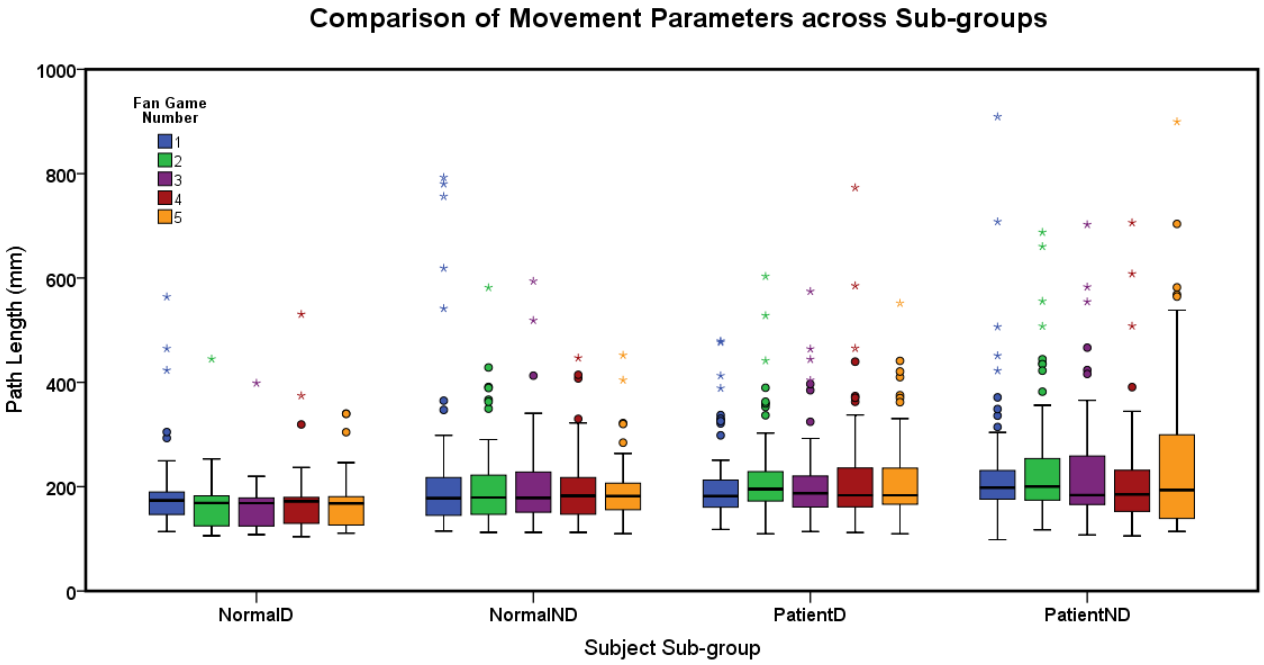
8.7 Appendix 5D - Boxplots of Tyneside Peg Test Data

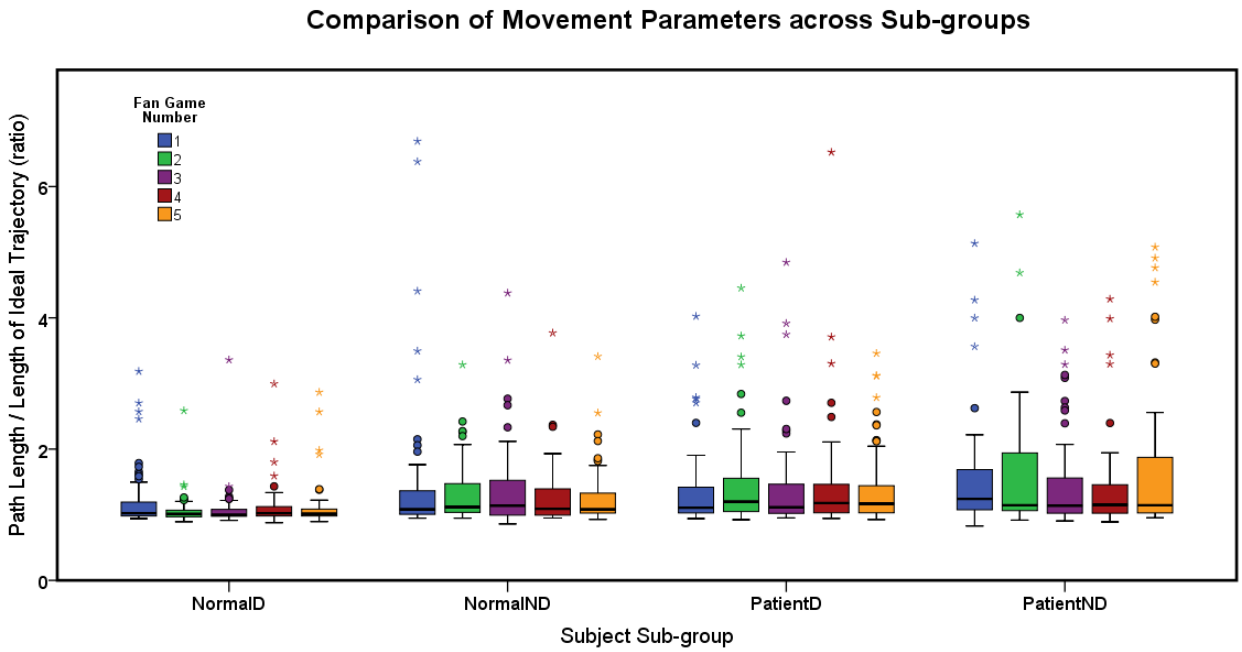


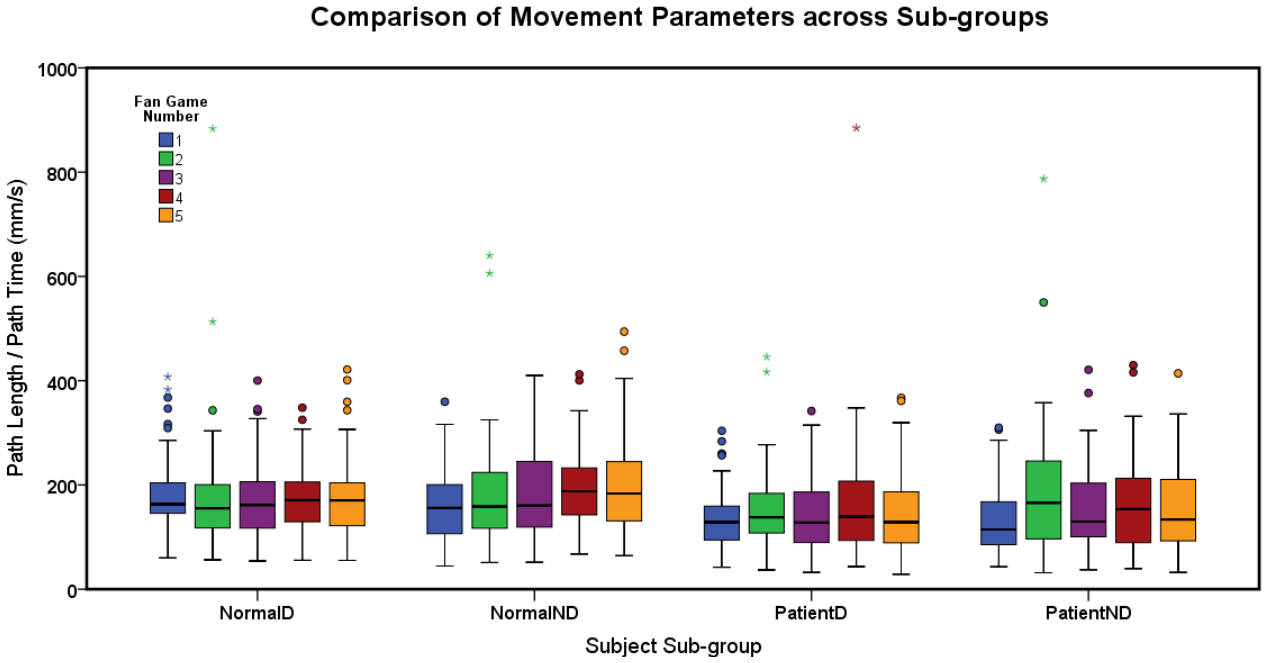


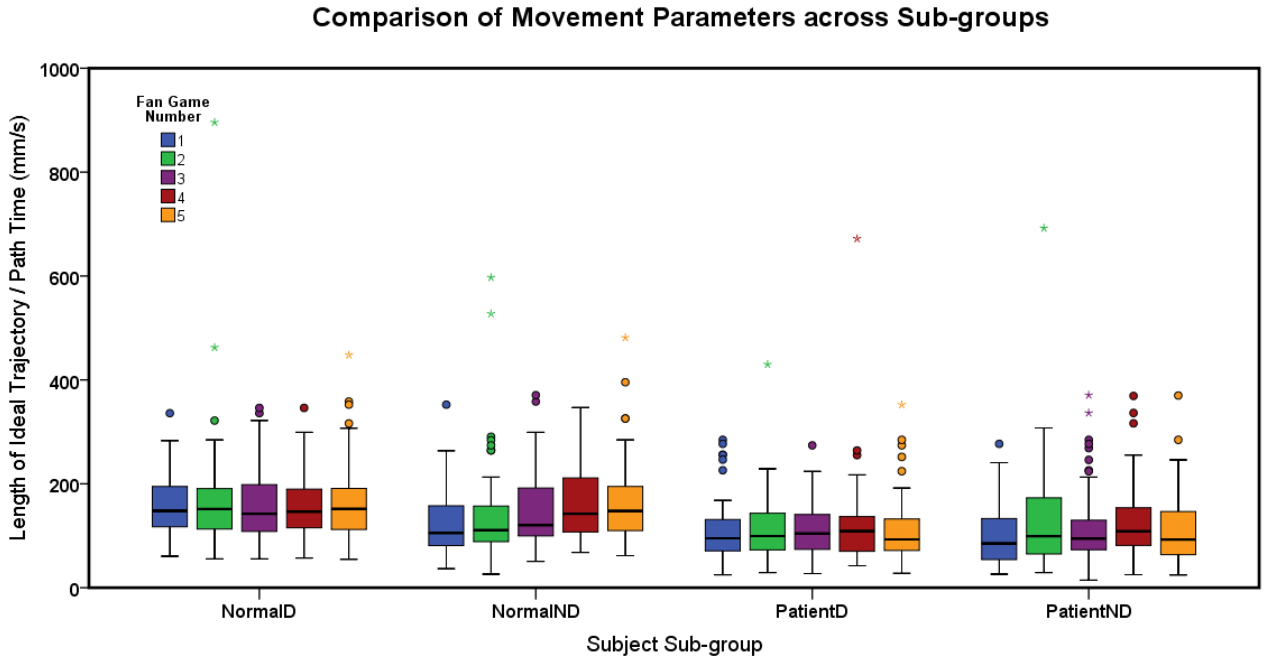
8.8 Appendix 5E - Boxplots of Movement Parameters

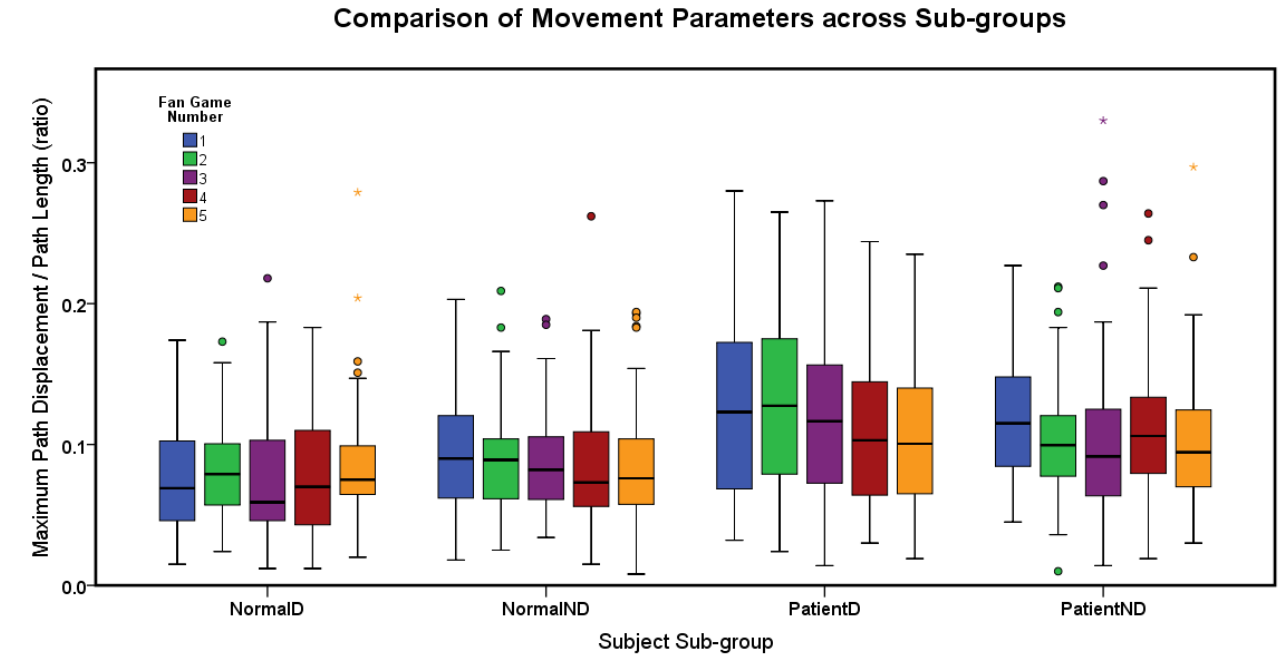


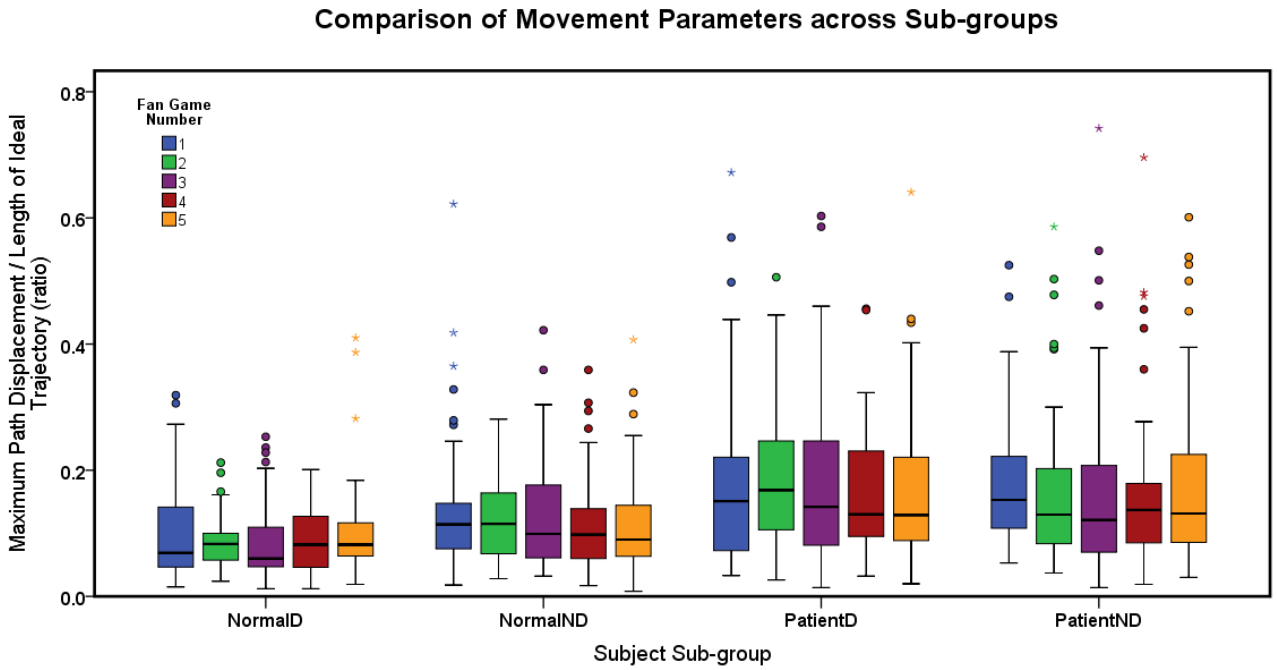


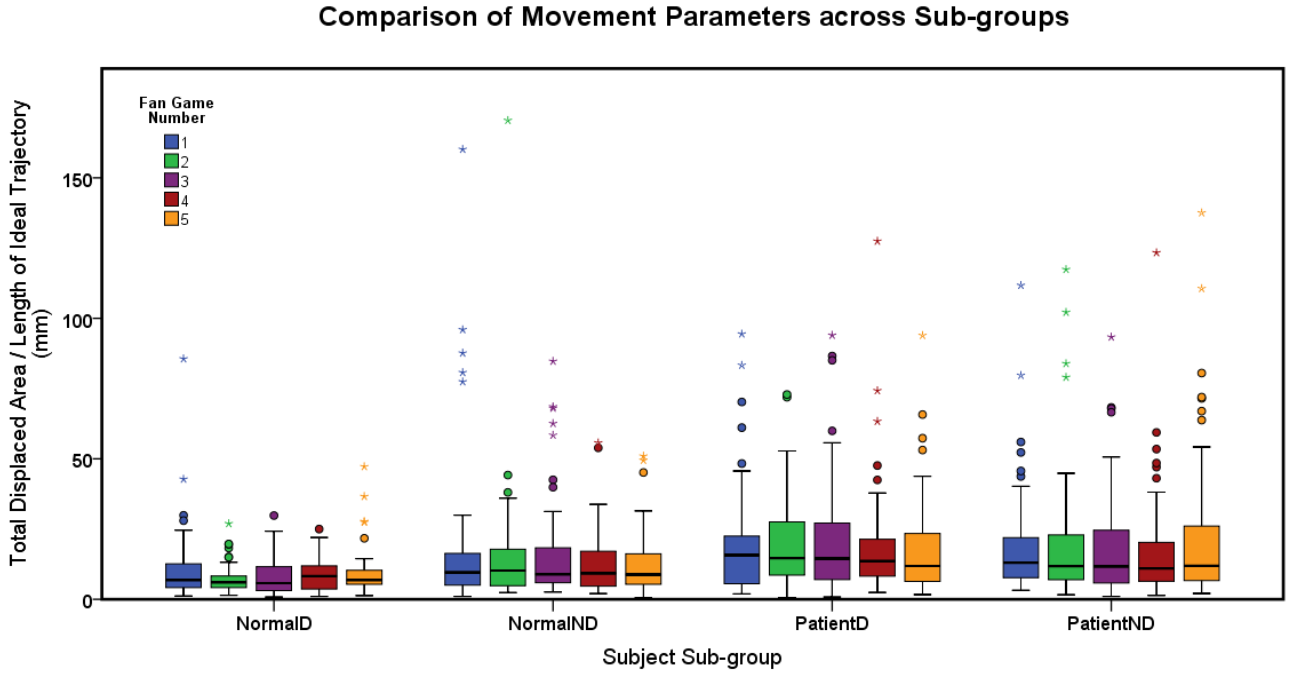

Comparison of Movement Parameters across Sub-groups
Fan Game Number
1
2
3
4
5
Path Length / Length of Ideal Trajectory (ratio)
0
2
4
6
NormalD
NormalND
PatientD
PatientND
Subject Sub-group

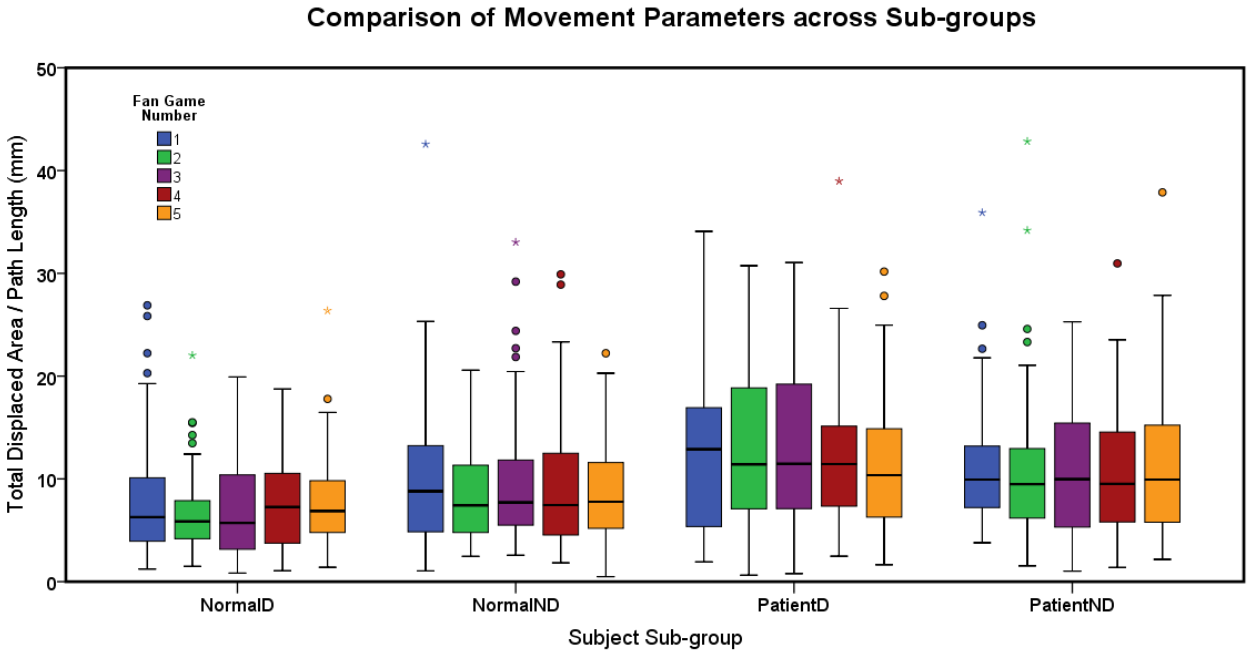

Comparison of Movement Parameters across Sub-groups
Fan Game Number
1
2
3
4
5
Path Length / Path Time (mm/s)
0
200
400
600
800
1000
NormalD
NormalND
PatientD
PatientND
Subject Sub-group

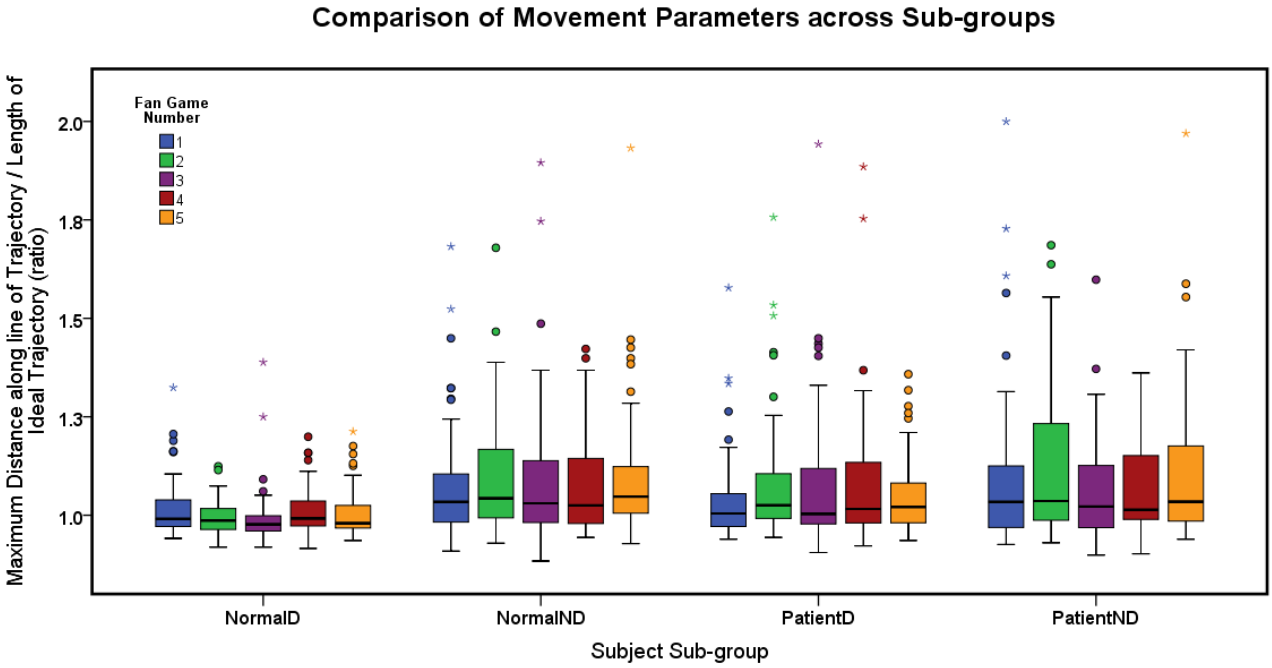

Comparison of Movement Parameters across Sub-groups
Fan Game Number
1
2
3
4
5
Length of Ideal Trajectory / Path Time (mm/s)
0
200
400
600
800
1000
NormalD
NormalND
PatientD
PatientND
Subject Sub-group

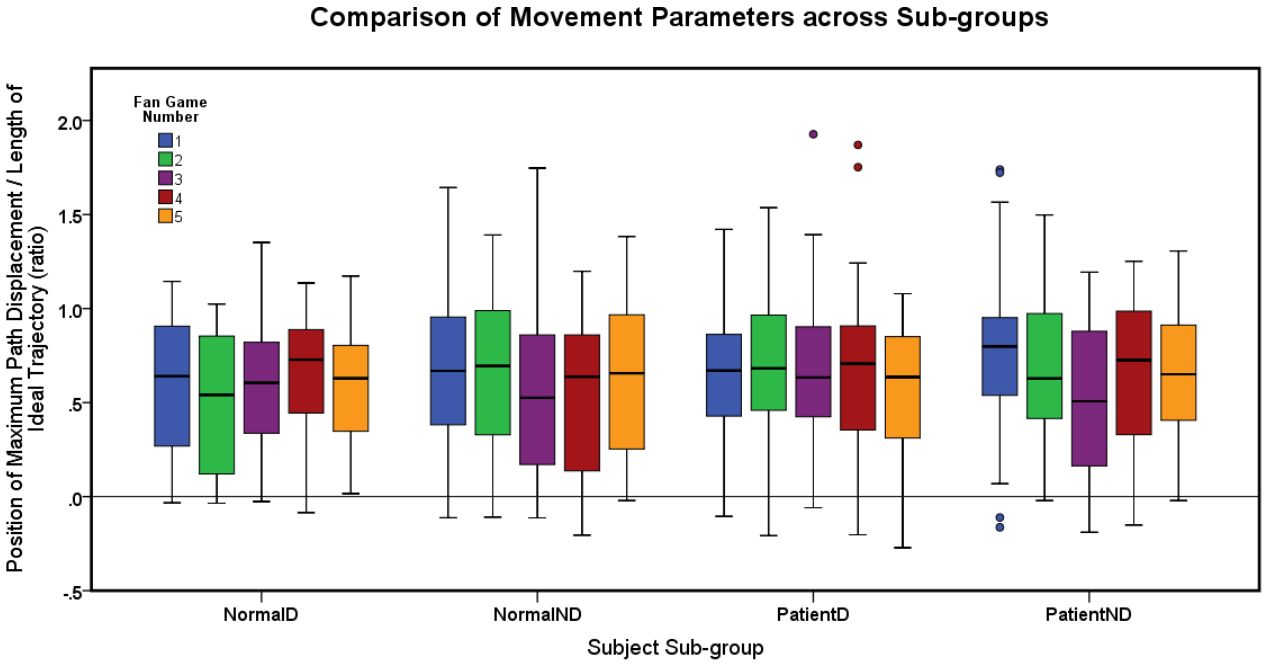

Comparison of Movement Parameters across Sub-groups
Fan Game Number
1
2
3
4
5
Maximum Path Displacement / Path Length (ratio)
0.0
0.1
0.2
0.3
NormalD
NormalND
PatientD
PatientND
Subject Sub-group

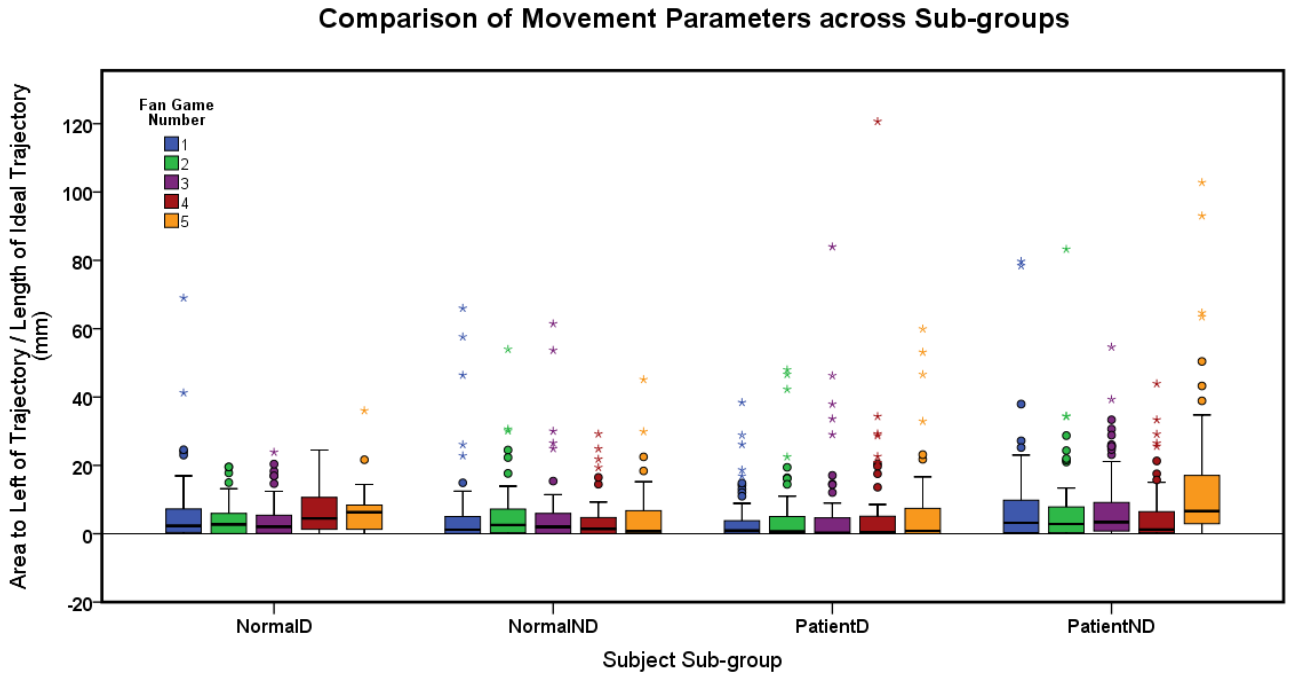

Comparison of Movement Parameters across Sub-groups
Fan Game Number
1
2
3
4
5
Maximum Path Displacement / Length of Ideal Trajectory (ratio)
0.0
0.2
0.4
0.6
0.8
NormalD
NormalND
PatientD
PatientND
Subject Sub-group

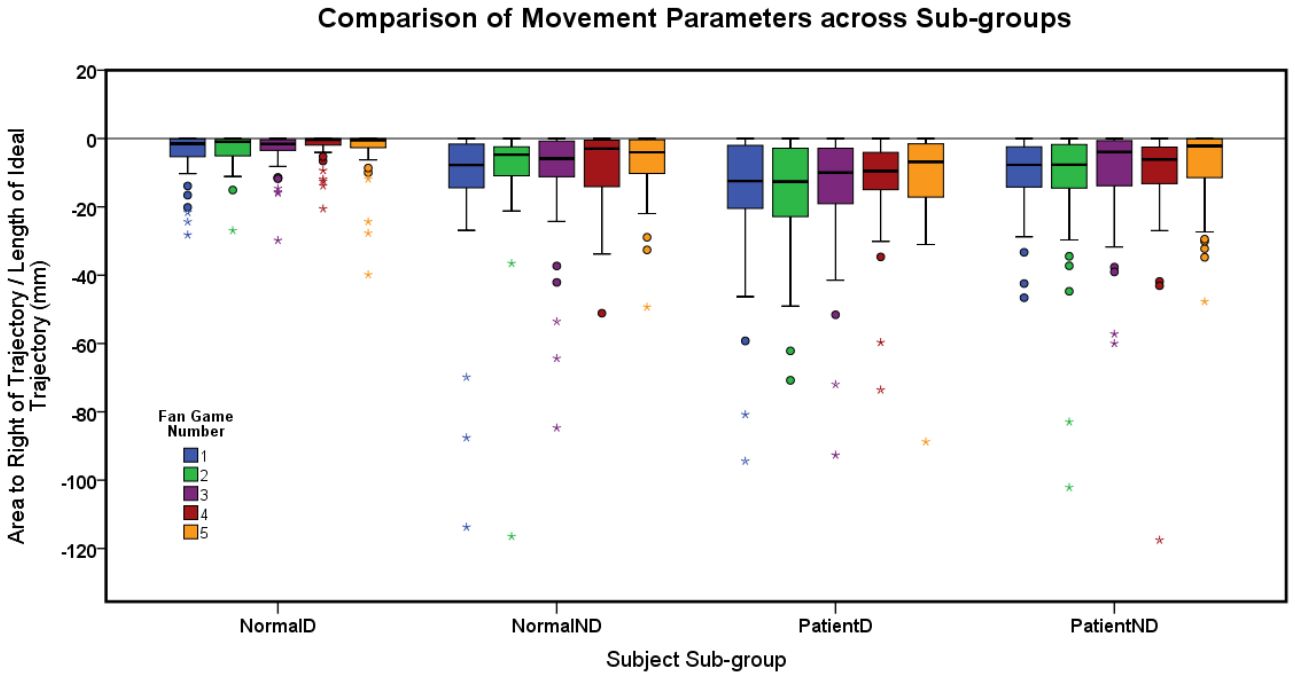

Comparison of Movement Parameters across Sub-groups
Fan Game Number
1
2
3
4
5
Total Displaced Area / Length of Ideal Trajectory (mm)
0
50
100
150
NormalD
NormalND
PatientD
PatientND
Subject Sub-group

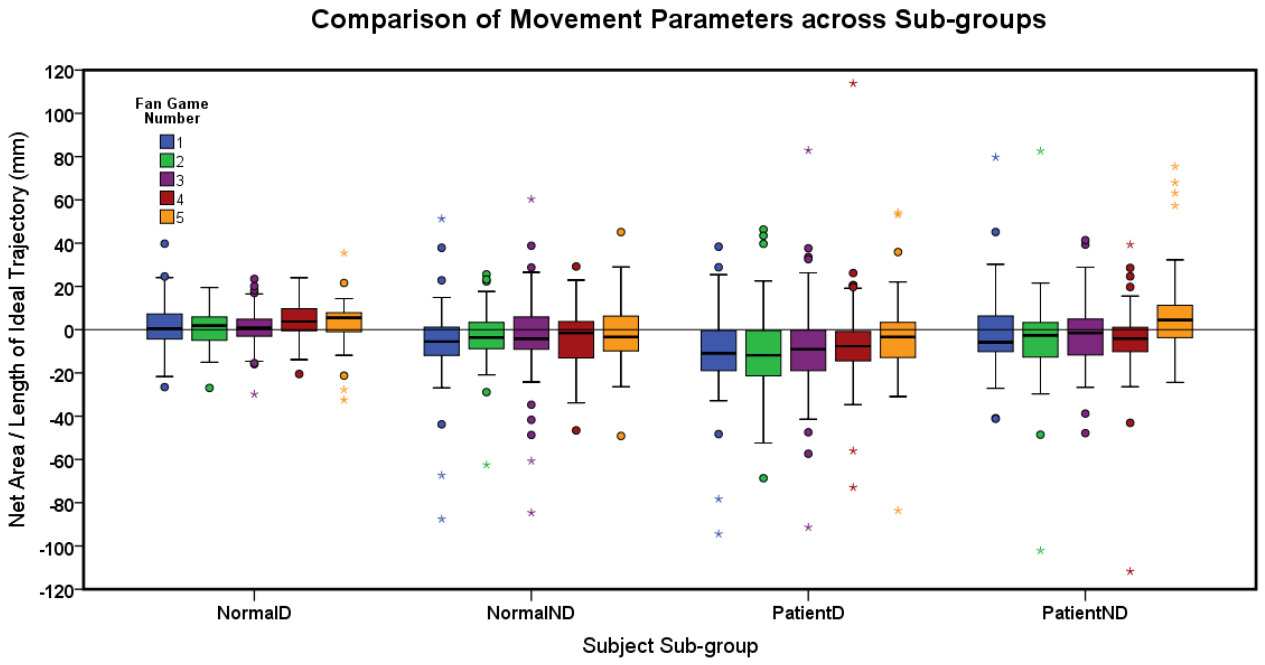

Comparison of Movement Parameters across Sub-groups
Fan Game Number
1
2
3
4
5
Total Displaced Area / Path Length (mm)
50
40
30
20
10
0
NormalD
NormalND
PatientD
PatientND
Subject Sub-group


Comparison of Movement Parameters across Sub-groups
Fan Game Number
1
2
3
4
5
Maximum Distance along line of Trajectory / Length of Ideal Trajectory (ratio)
2.0
1.8
1.5
1.3
1.0
NormalD
NormalND
PatientD
PatientND
Subject Sub-group


Comparison of Movement Parameters across Sub-groups
Fan Game Number
1
2
3
4
5
Position of Maximum Path Displacement / Length of Ideal Trajectory (ratio)
2.0
1.5
1.0
.5
.0
-.5
NormalD
NormalND
PatientD
PatientND
Subject Sub-group


Comparison of Movement Parameters across Sub-groups
Fan Game Number
1
2
3
4
5
Area to Left of Trajectory / Length of Ideal Trajectory (mm)
120
100
80
60
40
20
0
-20
NormalD
NormalND
PatientD
PatientND
Subject Sub-group


Comparison of Movement Parameters across Sub-groups
Fan Game Number
1
2
3
4
5
Area to Right of Trajectory / Length of Ideal Trajectory (mm)
20
0
-20
-40
-60
-80
-100
-120
NormalD
NormalND
PatientD
PatientND
Subject Sub-group


Comparison of Movement Parameters across Sub-groups
Fan Game Number
1
2
3
4
5
Net Area / Length of Ideal Trajectory (mm)
120
100
80
60
40
20
0
-20
-40
-60
-80
-100
-120
NormalD
NormalND
PatientD
PatientND
Subject Sub-group

8.9 Appendix 5F - Principal Component Analysis Data

PCA with used for Pre-selecting Parameters (SPSS - PCA: Varimax)

Normal Dominant - trimmed subject AH

Parameter	Component		
	1	2	3
Path Length / Length of Ideal Trajectory (ratio)	.782	-.200	.554
Path Length / Path Time (mm/s)	.328		.935
Length of Ideal Trajectory / Path Time (mm)		.104	.966
Maximum Path Displacement / Path Length (ratio)	.851	.313	
Maximum Path Displacement / Length of Ideal Trajectory (ratio)	.973		.192
Total Displaced Area / Length of Ideal Trajectory (mm)	.901		.379
Total Displaced Area / Path Length (mm)	.890	.290	.275
Maximum Distance along line of Trajectory / Length of Ideal Trajectory (ratio)	.357	-.144	.873
Position of Maximum Path Displacement / Length of Ideal Trajectory (ratio)	.578	.194	.431
Area to Left of Trajectory (mm2)	.521	.834	.108
Area to Left of Trajectory / Length of Ideal Trajectory (mm)	.412	.881	.184
Area to Right of Trajectory (mm2)	-.393	.806	-.407
Area to Right of Trajectory / Length of Ideal Trajectory (mm)	-.377	.813	-.409
Nett Area (mm2)	.270	.939	
Net Area / Length of Ideal Trajectory (mm)	.197	.950	

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 5 iterations.

Total Variance Explained

Component	Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %
1	5.3	35.4	35.4
2	4.9	32.5	67.9
3	3.7	24.7	92.5

Extraction Method: Principal Component Analysis.

Normal Non-dominant - trimmed subject AH

Parameter	Component		
	1	2	3
Path Length / Length of Ideal Trajectory (ratio)	.866		.168
Path Length / Path Time (mm/s)	.894	.233	.257
Length of Ideal Trajectory / Path Time (mm)	.610	.291	.141
Maximum Path Displacement / Path Length (ratio)	.241	-.334	.792
Maximum Path Displacement / Length of Ideal Trajectory (ratio)	.642	-.218	.721
Total Displaced Area / Length of Ideal Trajectory (mm)	.928	-.301	.131
Total Displaced Area / Path Length (mm)	.652	-.463	.472
Maximum Distance along line of Trajectory / Length of Ideal Trajectory (ratio)	.926	.129	.116
Position of Maximum Path Displacement / Length of Ideal Trajectory (ratio)			.884
Area to Left of Trajectory (mm2)	.960	.205	
Area to Left of Trajectory / Length of Ideal Trajectory (mm)	.980	.139	
Area to Right of Trajectory (mm2)		.963	-.204
Area to Right of Trajectory / Length of Ideal Trajectory (mm)		.982	
Nett Area (mm2)	.496	.823	-.255
Net Area / Length of Ideal Trajectory (mm)	.560	.771	-.250

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 5 iterations.

Total Variance Explained

Component	Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %
1	7.0	46.6	46.6
2	3.9	25.7	72.2
3	2.5	16.5	88.7

Extraction Method: Principal Component Analysis.

Patient Dominant - trimmed subject M

Rotated Component Matrix	Component		
	1	2	3
Path Length / Length of Ideal Trajectory (ratio)	-.444	.752	.308
Path Length / Path Time (mm/s)		.672	.700
Length of Ideal Trajectory / Path Time (mm)	.492		.827
Maximum Path Displacement / Path Length (ratio)	-.922		
Maximum Path Displacement / Length of Ideal Trajectory (ratio)	-.695	.660	.195
Total Displaced Area / Length of Ideal Trajectory (mm)	-.523	.834	-.154
Total Displaced Area / Path Length (mm)	-.679	.591	-.203
Maximum Distance along line of Trajectory / Length of Ideal Trajectory (ratio)	-.119	.903	.239
Position of Maximum Path Displacement / Length of Ideal Trajectory (ratio)		.838	
Area to Left of Trajectory (mm2)	.379	.659	.581
Area to Left of Trajectory / Length of Ideal Trajectory (mm)	.332	.661	.635
Area to Right of Trajectory (mm2)	.898	-.237	.333
Area to Right of Trajectory / Length of Ideal Trajectory (mm)	.933	-.219	.266
Nett Area (mm2)	.882		.408
Net Area / Length of Ideal Trajectory (mm)	.917		.357

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 8 iterations.

Total Variance Explained

Component	Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %
1	6.1	40.5	40.5
2	5.0	33.4	73.9
3	2.7	17.7	91.6

Extraction Method: Principal Component Analysis.

Patient Non-dominant - trimmed subject M

	Component		
	1	2	3
Path Length / Length of Ideal Trajectory (ratio)	.959	.165	.108
Path Length / Path Time (mm/s)	.767		.630
Length of Ideal Trajectory / Path Time (mm)		-.209	.943
Maximum Path Displacement / Path Length (ratio)	.613	-.454	-.524
Maximum Path Displacement / Length of Ideal Trajectory (ratio)	.952		-.254
Total Displaced Area / Length of Ideal Trajectory (mm)	.979	.152	
Total Displaced Area / Path Length (mm)	.959	-.104	-.148
Maximum Distance along line of Trajectory / Length of Ideal Trajectory (ratio)	.895	.171	.312
Position of Maximum Path Displacement / Length of Ideal Trajectory (ratio)	.602	.424	.133
Area to Left of Trajectory (mm2)	.903	.367	
Area to Left of Trajectory / Length of Ideal Trajectory (mm)	.904	.353	
Area to Right of Trajectory (mm2)	-.900	.375	-.114
Area to Right of Trajectory / Length of Ideal Trajectory (mm)	-.810	.496	-.112
Nett Area (mm2)		.956	-.119
Net Area / Length of Ideal Trajectory (mm)	.130	.964	

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 6 iterations.

Total Variance Explained

Component	Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %
1	9.0	59.7	59.7
2	3.0	20.1	79.8
3	1.8	12.2	92.0

Extraction Method: Principal Component Analysis.

The green shaded cells indicate loadings greater than 0.3 in the initial PCA and total variance greater than 75% for the given components.

8.10 Appendix 5G - Initial Regression Analysis

Initial Regression Analysis for Pre-selecting Parameters (SPSS - ALM: all predictors, no trimming)

Normal Dominant - trimmed subject AH	
Parameters	**Importance**
Maximum Distance along line of Trajectory / Length of Ideal Trajectory (ratio)	0.002
Length of Ideal Trajectory / Path Time (mm/s)	0.003
Path Length / Path Time (mm/s)	0.008
Maximum Path Displacement / Length of Ideal Trajectory (ratio)	0.046
Total Displaced Area / Length of Ideal Trajectory (mm)	0.080
Total Displaced Area / Path Length (mm)	0.106
Path Length / Length of Ideal Trajectory (ratio)	0.120
Maximum Path Displacement / Path Length (ratio)	0.163
Position of Maximum Path Displacement / Length of Ideal Trajectory (ratio)	0.473

Normal Non-dominant - trimmed subject AH	
Parameters	**Importance**
Maximum Distance along line of Trajectory / Length of Ideal Trajectory (ratio)	0.035
Maximum Path Displacement / Path Length (ratio)	0.065
Total Displaced Area / Path Length (mm)	0.070
Total Displaced Area / Length of Ideal Trajectory (mm)	0.072
Maximum Path Displacement / Length of Ideal Trajectory (ratio)	0.072
Position of Maximum Path Displacement / Length of Ideal Trajectory (ratio)	0.074
Path Length / Path Time (mm/s)	0.121
Length of Ideal Trajectory / Path Time (mm/s)	0.197
Path Length / Length of Ideal Trajectory (ratio)	0.294

Patient Dominant - trimmed subject M	
Parameters	**Importance**
Position of Maximum Path Displacement / Length of Ideal Trajectory (ratio)	0.046
Area to Left of Trajectory (mm2)	0.059
Maximum Distance along line of Trajectory / Length of Ideal Trajectory (ratio)	0.089
Path Length / Length of Ideal Trajectory (ratio)	0.096
Length of Ideal Trajectory / Path Time (mm/s)	0.110
Total Displaced Area / Path Length (mm)	0.112
Maximum Path Displacement / Length of Ideal Trajectory (ratio)	0.112
Path Length / Path Time (mm/s)	0.115
Maximum Path Displacement / Path Length (ratio)	0.116
Total Displaced Area / Length of Ideal Trajectory (mm)	0.1452

Patient Non-dominant - trimmed subject M	
Parameters	**Importance**
Total Displaced Area / Length of Ideal Trajectory (mm)	0.026
Total Displaced Area / Path Length (mm)	0.040
Maximum Path Displacement / Path Length (ratio)	0.059
Path Length / Length of Ideal Trajectory (ratio)	0.159
Maximum Path Displacement / Length of Ideal Trajectory (ratio)	0.203
Length of Ideal Trajectory / Path Time (mm/s)	0.249
Path Length / Path Time (mm/s)	0.263

The green shaded cells indicate higher importance from the initial regression analysis and hence suitability for use as good indicators of potential parameters.

8.11 Appendix 5H - Basis of New Metric

Median Values for Pre-selected Parameters (green highligted parameters used in metric)																
Sub-Group	SubjectID	PL/LIT	PL/PT	LIT/PT	MPD/PL	MPD/LIT	TDA/LIT	TDA/PL	MDLoT/LIT	PMPD/LIT	ALHS	ALHS/LIT	ARHS	ARHS/LIT	NA	NA/LIT
NormalD	AA	0.99	111	115	0.07	0.07	5.88	5.94	0.97	0.34	232	1.65	-169	-1.18	48	0.41
	AB	1.20	254	185	0.08	0.11	12.27	8.30	1.01	0.85	268	1.56	-674	-4.84	-142	-0.80
	AC	0.98	119	121	0.08	0.08	5.03	5.28	0.97	0.57	582	3.56	-31	-0.17	447	3.50
	AD	0.98	133	133	0.07	0.07	4.76	4.84	0.97	0.58	367	2.16	-242	-1.61	215	1.21
	AE	1.06	167	157	0.10	0.10	7.94	7.22	1.00	0.67	858	5.10	-109	-0.63	400	2.26
	AF	1.14	196	161	0.10	0.12	14.02	11.41	0.99	0.75	1426	8.62	-88	-0.50	1347	8.28
	AG	0.99	174	176	0.05	0.05	3.66	3.74	0.98	0.54	418	2.36	-67	-0.38	390	2.27
	AI	1.05	182	168	0.06	0.07	5.71	5.14	0.99	0.29	369	2.35	-252	-1.85	89	0.50
	AJ	0.97	73	76	0.06	0.06	4.30	4.49	0.96	0.56	449	3.01	-73	-0.42	431	2.88
	AK	1.01	205	200	0.06	0.06	6.34	6.36	1.00	0.70	745	6.24	-47	-0.27	737	6.02
NormalND	AA	1.03	121	109	0.09	0.11	8.89	8.80	0.98	0.62	59	0.50	-848	-4.78	-687	-3.87
	AB	1.61	247	158	0.07	0.13	17.95	8.58	1.24	0.56	1126	7.59	-494	-2.79	665	5.62
	AC	1.00	127	117	0.07	0.07	6.71	5.93	0.98	0.53	83	0.70	-560	-4.30	-471	-3.27
	AD	1.01	114	111	0.08	0.09	5.30	5.23	0.98	0.66	51	0.42	-691	-4.50	-573	-3.34
	AE	1.31	188	135	0.12	0.16	10.83	8.79	1.08	0.75	659	3.95	-513	-2.90	-226	-1.91
	AF	1.13	181	157	0.11	0.14	15.28	10.70	1.07	0.65	526	3.88	-1368	-8.51	-1051	-6.94
	AG	1.03	178	182	0.08	0.08	7.58	6.83	1.00	0.41	456	3.29	-466	-3.57	-10	-0.08
	AI	1.33	169	123	0.09	0.13	11.32	8.47	1.08	0.77	238	2.01	-1343	-7.80	-1207	-7.16
	AJ	0.99	80	82	0.06	0.06	4.43	4.35	0.98	0.52	11	0.07	-520	-4.12	-516	-4.11
	AK	1.10	210	185	0.08	0.11	7.59	6.96	1.08	0.78	368	2.46	-316	-2.20	37	0.31
PatientD	A	1.26	90	66	0.13	0.19	24.49	14.55	1.07	0.79	10	0.06	-3321	-21.60	-3321	-20.76
	B	1.06	120	109	0.08	0.08	5.46	4.91	1.00	0.18	279	1.62	-276	-1.60	-65	-0.37
	C	1.10	165	145	0.09	0.13	9.47	7.58	1.03	0.73	776	5.27	-204	-1.44	627	3.82
	D	1.03	122	109	0.08	0.08	7.77	7.21	0.99	0.54	37	0.21	-959	-5.41	-958	-5.40
	E	1.18	121	95	0.14	0.17	17.85	14.04	1.01	0.59	24	0.13	-2632	-17.49	-2584	-16.47
	F	1.96	225	101	0.14	0.29	29.27	16.60	1.15	0.72	728	5.06	-3383	-22.47	-2550	-17.33
	G	1.03	108	97	0.11	0.11	12.30	11.48	0.98	0.45	0	0.00	-1910	-12.11	-1910	-11.90
	H	1.09	100	97	0.15	0.16	15.10	15.13	0.99	0.57	4	0.04	-2244	-14.96	-2239	-14.93
	J	1.36	172	102	0.08	0.16	21.71	14.19	1.06	0.89	640	3.72	-740	-4.18	636	3.70
	K	1.37	176	119	0.15	0.21	16.38	12.96	1.02	0.78	226	1.91	-1619	-13.68	-1150	-9.71
	L	1.36	210	132	0.11	0.16	19.37	12.10	1.13	0.86	1492	8.42	-920	-5.62	45	0.25
PatientND	A	1.20	93	71	0.09	0.16	11.53	9.77	1.02	0.72	857	5.67	-614	-3.47	-31	-0.18
	B	1.05	108	98	0.10	0.10	7.04	6.61	1.00	0.44	345	2.02	-408	-2.97	-253	-1.71
	C	1.70	174	94	0.12	0.18	22.64	14.20	1.14	0.60	689	5.06	-1448	-8.17	-733	-4.27
	D	1.02	112	113	0.06	0.06	4.02	3.90	0.98	0.40	285	2.41	-231	-1.88	63	0.53
	E	1.30	87	64	0.12	0.18	14.88	10.02	1.02	0.77	728	4.75	-862	-5.67	-309	-2.61
	F	1.67	254	142	0.09	0.15	22.29	10.13	1.19	0.84	1102	6.50	-1421	-8.02	-784	-4.56
	G	1.04	120	112	0.10	0.11	9.08	8.47	0.98	0.36	292	1.65	-819	-4.62	-389	-3.26
	H	1.03	114	106	0.09	0.09	8.53	8.23	0.99	0.65	57	0.32	-965	-7.40	-881	-7.24
	J	1.11	162	140	0.08	0.10	9.11	7.45	1.03	0.84	346	2.39	-339	-2.08	-69	-0.47
	K	1.42	214	135	0.11	0.19	18.60	13.13	1.07	0.53	829	5.29	-2027	-14.36	-1674	-10.43
	L	2.10	250	109	0.10	0.25	38.74	16.91	1.23	0.96	2034	11.48	-1952	-11.35	1010	5.98

Weighted Parameters (to maximise sub-group correlation) forming New Metric													
	SubjectID	Sum of weighted parameters	PL/PT	LIT/PT	MPD/LIT	TDA/PL	PMPD/LIT	**Calculated Metric**	TPT Data	**Correlation with TPT Data and Predicted TPT**	MA2 Data	**Correlation with MA2**	**Correlation with all TPT data for all Sub-groups**
NormalD	**Weighting**	**171**	**0.04**	**-0.10**	**-0.18**	**0.19**	**0.04**						
	AA	13.1	2.22	3.25	2.79	2.78	2.11	**-0.11**	12				
	AB	24.0	5.06	5.21	4.60	3.89	5.20	**-0.19**	11.9				
	AC	14.9	2.38	3.41	3.08	2.48	3.53	**-0.18**	12.2				
	AD	15.0	2.64	3.75	2.75	2.27	3.55	**-0.18**	12				
	AE	19.4	3.33	4.43	4.11	3.39	4.14	**-0.23**	11.7	**0.87**	n/a	n/a	
	AF	23.5	3.89	4.53	5.09	5.35	4.60	**0.00**	12.8				
	AG	15.4	3.47	4.96	1.85	1.75	3.32	**-0.21**	11.5				
	AI	15.2	3.62	4.72	2.67	2.41	1.78	**-0.26**	11.9				
	AJ	11.5	1.45	2.15	2.38	2.11	3.43	**-0.04**	12.7				
	AK	19.5	4.07	5.63	2.50	2.98	4.31	**-0.09**	12.6				
NormalND	**Weighting**	**207**	**0.08**	**-0.13**	**-0.14**	**0.16**	**0.03**						
	AA	19.7	2.54	3.41	3.58	4.77	5.39	**0.13**	13.8				
	AB	24.0	5.18	4.96	4.30	4.65	4.86	**0.00**	13.7				
	AC	16.7	2.68	3.69	2.52	3.21	4.55	**-0.02**	14.9				
	AD	17.3	2.39	3.48	2.90	2.84	5.71	**-0.09**	12.7				
	AE	24.7	3.94	4.22	5.32	4.77	6.46	**-0.08**	13.7	**0.61**	n/a	n/a	
	AF	24.8	3.80	4.93	4.67	5.81	5.60	**0.04**	15.1				
	AG	19.5	3.74	5.70	2.83	3.70	3.52	**-0.20**	11.7				
	AI	23.0	3.54	3.86	4.40	4.59	6.65	**0.04**	13				
	AJ	13.2	1.68	2.59	2.01	2.36	4.52	**-0.01**	14.2				
	AK	24.4	4.40	5.80	3.65	3.77	6.76	**-0.18**	13.1				
PatientD	**Weighting**	**177**	**-0.17**	**0.01**	**0.10**	**0.10**	**0.09**						**0.92**
	A	16.6	2.07	3.32	3.21	4.08	3.97	**0.79**	18.9		62		
	B	11.9	2.75	5.51	1.34	1.38	0.89	**-0.05**	12.6		58		
	C	19.1	3.78	7.32	2.21	2.12	3.66	**0.21**	14.3		67		
	D	14.4	2.80	5.50	1.38	2.02	2.71	**0.18**	12.7		88		
	E	17.5	2.79	4.82	2.96	3.93	2.98	**0.55**	19.9		21		
	F	23.6	5.18	5.13	5.05	4.65	3.62	**0.49**	15.7	**0.67**	34	**-0.14**	
	G	14.8	2.47	4.90	1.96	3.21	2.25	**0.37**	12.3		66		
	H	17.1	2.30	4.93	2.79	4.24	2.87	**0.65**	16.8		90		
	J	20.4	3.94	5.18	2.79	3.97	4.49	**0.48**	14.6		82		
	K	21.2	4.05	6.03	3.58	3.63	3.91	**0.47**	12.5		57		
	L	22.0	4.82	6.68	2.79	3.39	4.31	**0.27**	16.6		72		
PatientND	**Weighting**	**152**	**-5.13**	**1.49**	**3.49**	**0.26**	**-0.19**						
	A	14.1	1.58	2.91	3.03	2.78	3.81						
	B	12.0	1.83	4.02	1.93	1.88	2.31	**3.41**	35.2		58		
	C	17.3	2.96	3.84	3.27	4.04	3.17	**2.40**	31.5		67		
	D	10.9	1.91	4.63	1.13	1.11	2.13	**0.97**	27.3		88		
	E	14.3	1.48	2.61	3.31	2.85	4.07						
	F	20.3	4.31	5.83	2.85	2.88	4.45			**0.71**		**-0.65**	
	G	12.9	2.03	4.58	1.95	2.41	1.90	**3.49**	53.1		66		
	H	13.7	1.95	4.33	1.67	2.34	3.45	**2.28**	28.4		90		
	J	16.8	2.76	5.72	1.77	2.12	4.42	**0.26**	22.8		82		
	K	19.2	3.64	5.51	3.55	3.74	2.78	**2.41**	27.2		57		
	L	23.3	4.25	4.45	4.69	4.81	5.06	**1.48**	34.4		72		

8.12 Appendix 6A - Technical Limitations with Prototype 1

This appendix documents the most important technical limitations identified with prototype 1 and potential solution to these.

Hardware
The hardware for prototype 1 was very simple and required only basic manufacturing processes to integrate the mouse and other bought-in items such as bearings. Only a custom skate and playing surface were required with simple springs to hold the skate in position relative to the measurement axes of the mouse, which was contained within the skate. A low friction surface was produced using thin PTFE sheet over a fibreboard base.

The skate and hardware arrangement noted in section 4.4 proved more than adequate for the fan-game assessments and appeared to be well received by the users who found it easy to hold and move to play the games.

There were a few durability issues with the low friction surface and mouse cable, which needed to be moved away from the playing surface periodically to avoid fouling the skate. Similarly, it was possible to inadvertently touch the springs during gameplay and this would have affected positional measurement. The thin PTFE sheet was held to the fibreboard base with adhesive which would not last with repeated use. Similarly, there was a limitation on available sheet sizes and joins were required which had the potential to obstruct the skate or trap dust and dirt which would have been difficult to clean. Physical risks to the users were minimal.

Solutions to these hardware limitations were relatively straightforward. A solid sheet of ultra-high molecular weight polyethylene (UHMWPE) could be used to cover the baseboard or, if sufficiently thick, could be used as the baseboard itself. UHMWPE is commonly used as low friction material in limb joint replacements and hence has negligible approval issues. The mouse cable could be held on a support spring to the rear of the playing surface and away from the screen. The tension springs were linked to the need to hold the skate in position and were discussed in section 4.4.

Sensors
The primary sensor was the mouse (housed in the skate) which detected relative motion from a known start point. This start point was the “home” that appeared on the VRE and was reset before each new fan-game. There were potential issues with the mouse as it required contact with the surface to operate the rotary encoders. If contact was lost (which was not actually observed during the laboratory or clinical tests) subsequent measurements would be invalid. The mouse and encoders were extremely reliable and cost-effective sensors but required the spring field to prevent deliberate or inadvertent rotation.

The solution was less simple than for the playing surface and required a redesigned skate and draw-wire sensors. The skate would be held in a similar spring field to that of prototype 1 but provided by four matched draw-wires coupled to precision rotary potentiometers. The positional accuracy and repeatability of the draw-wire sensors was superior to the mouse and they also provided a more secure method for retaining the skate on the playing surface.

Software

The PC-based software interfaces suffered from a number of issues including uncontrollable interrupts in data transfer, data clusters and random instabilities in the VRE. All of these issues were overcome by manually assessing each data set and discarding spurious data points as discussed in section 4.4. There were also some issues with target acquisition and prompting new targets to appear. As the trigger point for the next target was not always the same point (defined by an overlapping of the cursor and Home Base) the start point for each outbound leg was not always easily defined. The start point was also unclear when a few participants (patient and normal) hesitated or became distracted. Further, the software sometimes failed to show a target when the home base was reached unless the mouse moved slightly away it. The start point within the data sets was therefore standardized (and adjusted manually) as the start of continued motion (in any direction) after the cursor had passed within a fixed radius of the Home base. Earlier observations had demonstrated that once an outbound path was initiated the participant rarely returned to the home base although they might execute a very inefficient pathway to the targets.

Virtual Reality Environment

The VRE used with prototype 1 was basic but satisfactory, having been assessed successfully with concept B. Users found it easy to interpret and no apparent errors were made due to lack of understanding of audio-visual prompts or resulting paths shown on the screen. The VRE and reaching tasks were hard-coded into the software and only allowed filename modification which was specific to the participant.

An enhanced VRE and interface was required to allow more games to be developed to present more challenges to participants and to assess more potential parameters. The graphics were required to be kept simple to minimise distraction during game play but the whole environment might be changed to suit different users. This might be achieved by building a library of suitable graphics to suit children and adults, or male and female.

Data Integrity

The “simple” task of gathering reliable real-time data within a VRE proved to be a significant issue throughout this project. From the literature it would appear that this has also limited progress in a number of other better-resourced projects. In this project the extent of the objectives were modified (limiting to 2-D) rather than compromising the quality of data produced. As noted earlier a system redesign was required which maintained the objectives for a scalable and automated system.

It is clear from the literature that despite the apparent processing capability of commercial games that appear to act in real-time, considerable modification, interpolation and extrapolation of data is carried out to enhance game play rather than preserve data accuracy. In ARMaT devices, quantifiable data is required to provide a sensitive measure of progress and/or effect. Data used and re-interpreted for fast game play is unlikely to be sufficient for the interpretation of rehabilitation. However, the raw data from these cheap yet sophisticated devices combined with meaningful activities to assess ability may prove valuable.

The recent interest in using the exciting capabilities of personal mobile devices to promote exercise has also encouraged researchers and developers to look at these devices to promote rehabilitation through exercise. The ready availability and apparent sophistication of commercial games and hardware flooding the market appears to provide a low-cost solution

for assessment. This is very attractive and some valuable results may be achieved. However, data from these systems is entirely qualitative and cannot be scaled or interpreted across subjects. Results based upon these data should be treated with caution.

8.13 Appendix 6B - Development of Prototype 2

This appendix documents the most important developments for prototype 2 introduced in section 4.5 and discussed in section 7.2. based upon the technical limitations of prototype 1.

Playing Surface
Prototype 2 was re-designed with another solid base of veneered particle board to support a solid low-friction surface. This surface was made from ultra-high molecular weight polyethylene (UHMWPE) as it offered a low coefficient of friction and was already in use in medical environments. It is non-absorbing, readily cleaned and essentially inert in contact with human skin and fluids. It is substantially cheaper than the more commonly used polytetrafluoroethylene (PTFE) or nylon, which is also hydroscopic. The finished surface of the UHMWPE contained cutting marks which were essentially uni-directional. These were removed and any remaining marks from finishing were observed to be random in nature and minor in depth. The supporting board was fitted with foam feet to prevent unwanted movement on any table and to elevate the underside to allow fixings to auxiliary equipment.

Although the playing surface was inherently low-friction, the interface with the skate was modified from that used in prototype 1. There was still some limited evidence that the skate was rotating in use and this would cause some avoidable errors in the XY positional data due to an angular rotation of the path data from the true path.

The contact points with the playing surface were changed from flat nylon feet to polished steel ball bearings. These were held captive against vertical springs to minimise any asymmetric loading, and hence any potential asymmetry of motion due to differential friction. Five spring-ball units were equi-spaced on the same pitch circle diameter near the edge of the circular base of the skate.

Addition of Draw-wire sensors
Concept B identified the need to isolate user rotation from the skate. This was achieved with prototype 1 by suspending the skate in a simple spring-field formed by four low stiffness springs. The tension was adjusted to limit any rotation such that the tangential restoring forces from the springs were greater than the friction between the skate cover and the base.

The resolution of position obtained from the mouse data was more than that required to meet the demands on the device for positional accuracy and reliability. However, the data clustering, noted in section 4.4 was unacceptable and was indicative of a profound limitation with the simple PC-based design.

So many features were to be changed that a totally different geometry could be adopted. After considerable review, the advantages of the simple arrangement developed with prototype 1 were seen to be significant. Elements required re-design but most of the system had proved reliable and robust in use with patients in a clinical environment. Hence, new positional sensors were required to replace the mouse. The low-stiffness springs could be retained but these had been subject to some minor criticism regarding potential snagging of patient clothing, so another solution was sought.

In reviewing available sensors, draw-wire units were considered to be the most robust and useful, having adequate resolution and more than adequate accuracy (see section 3.2). Used extensively in the automotive industry, their ability to withstand a wide variety of forces and

harsh environments had been demonstrated. They also contained their own restoring springs which provide near-linear tension over their working range. Three such devices could be used to establish the minimum requirements of two fixed measuring stations and a suitable spring field. However, four units provided a more uniform spring-field and also allowed duplicate measurements to be made by using the second pair as well as the primary sensors. If required this would permit differential position measurements to be averaged to either determine a position with greater accuracy or to confirm positional data. A further consideration was the potential to include a Z-axis measurement although this was not planned for prototype 2.

In order to prevent the skate moving too far and potentially leave the playing surface and damaging the sensors, a border was formed around the surface. This supported the protection of the draw-wire sensors so that, in normal use, they could not be over extended. This is the only potential issue with these sensors but their advantages were considerable over other solutions.

Safe Handle Release

It had been noted that all patients needed to be able to release themselves from the handle readily and easily. This may be for personal hygiene reasons, lack of attention, or concern over perceived safety. The skate is concept B and prototype 1 was fitted with a simple handle that provided adequate grip opportunities for the wide range of patients tested. Release was possible as the handle was attached with hook-and-loop tape. For prototype 2, the arrangement of the handle and skate cover on top of the skate base allowed for the whole cover to be removed if the patient could not release the handle promptly. The requirements for safe release were met although removing the table exposed the accelerometer. As all wiring is low-voltage and current limited this was not considered an issue. The development of any production device will address any issues that might arise from exposed electronics.

Potential Participants

As the prototype exerts no significant forces and all sessions were supervised no special safety requirements were necessary. The device is effectively a large PC mouse held by some wires and represents no greater hazard to people than a standard PC mouse. All device voltages are low (3V3 to 5V0) and current limited. Any failure of a wire or device would result in minimal disruption and the potential for harm was considered negligible.

Skate Stability

The skate in prototype 1 was subjected to various forces, some of which are undesirable as they could rotate or elevate the mouse and hence affect the readings. This was rarely observed in supervised sessions but could be anticipated to occur. It was possible to overturn the skate when it was suspended by four light springs. This would not only give false data for X and Y but also potentially impose an artificial rotation. The skate for prototype 2 was redesigned to maintain a very low centre for the attachment of the spring field. This resisted overturning movements imposed through the handle. It also ensured that the springs (part of the draw-wire sensors) were maintained very close to the playing surface and hence less prone to interference between the user and the hardware.

Basis of Control System

The earlier issues with data-control and capture (discussed in section 4.4) were solved by a complete redesign of the main controller to include a PIC which interfaces with the software within the PC, and a change of Operating System (OS) from Windows to Linux. The process

of developing a suitable PIC interface took a considerable amount of time and also included an unreported prototype which continued to consider the mouse at the positional measurement device. Given this significant change a new PIC was sought. Developments in PICs, in particular digital signalling PICs (DSPICS) allowed significantly increased processing power and functionality to be used. Taking this opportunity, additional features were built into the new main controller to incorporate the accelerometer data, as well as enhanced resolution on the ADC for the draw-wire sensors. As the new DSPIC was capable of additional inputs and outputs (I/O) a new board was designed to allow further sensors and actuators to be added, if required in the future, without significant redesign of the main board.

All of the PIC and PC software development, main PIC board, peripheral sensors and communications were carried out by Ben Sherlock working within the RCID. The author worked closely with Ben to determine the functionality required from the system and to plan and assess the development of new features.

8.13.1 Anticipated Useful Data Sets

An ideal metric for rehabilitation progress would be one that has universal application and strong correlation with a number of clinical scales. This ideal has not been identified in the literature to date and may not actually exist. The most valuable metric for an individual is probably unique to them at any point in time. This would be established at first assessment as a baseline against which progress, or lack thereof, can be measured. Relative measures rather than absolute values are more suited to this approach.

From the data obtained with prototype 1 a number of potentially useful parameters could have been calculated within the PC software and included in the data output file. All of this data was derived from the raw X and Y positional data from the draw-wire sensors. However, processing speed remained a limitation so raw data was exported. The additional accelerometer data (X, Y, Z) was similarly recorded without modification so that any details contained within the data could be examined.

Typically, accelerometer data requires filtering and smoothing in order to obtain stable values. However, as with the X and Y positional data, it was noted that considerable detail may be lost in these processes before any assessment of their potential worth has been made. This is a significant issue with commercial sensors, especially gaming devices with their own software drivers as noted in section 2.6. The output is optimised for game play rather than faithful and accurate real-time recording. The emphasis of the game is the visual environment and only approximate motions are needed to fulfil this need.

8.13.2 Game Design

Having identified the key parameters using prototype 1, the game design in prototype 2 was enhanced to reflect the potential clinical application which would require more games in order to:

- Maintain interest
- Provide variety of challenge
- Provide levels of challenge
- Allow free-form games

A number of games were devised which built upon the symmetry valued from the original Fan-game, exploring either side of the playing surface using various angles and path lengths. The enhanced facilities in the new software will allow virtually any trajectory to be defined within the playing surface. This will permit not just rectilinear trajectories but pseudo-curves formed from straight lines. Hence, a user could be challenged with any trajectory set from a simple fan or box to a complex spiral design which might assess both large ballistic movement and subtle fine motor control within the same game.

The following game types were established as a bank of potential games to assess with healthy participants:

- Fan-game – baseline comparator with Prototype 1
- Square – basic geometrical structure testing orthogonal movements on primary axes
- Pentagon – extension from Square to assess non-orthogonal movements for comparison with the Square Game
- Circle – pseudo-circular motion to assess limited periodic measurements
- Figure 8 – extension to Circle
- Cruciform – inversion of Square and comparable to extended Fan

It was anticipated that these types, together with scaled versions of each would allow a wide range of healthy motion to be assessed with a view to establishing an initial set for clinical trials.

Potential Safety Issues

The board supporting the playing surface has been redesigned using a complete covering of UHMWPE to remove any potential for contamination. This material is sufficiently stiff and strong enough to support ancillary equipment using standard mechanical fixings. The only manufacturing limitation is the use adhesives which is impractical due the required low-friction and non-absorbing properties.

The draw-wire sensors require a fine, flexible and non-abrasive cable to be connected to the skate from each corner. Whilst the wire is inert and light, there is a potential for a user to catch clothing or their arm. This would most likely result in a false data set rather than any minor injury. This would need to be identified and monitored with any therapist or carer conducting the testing.

Limitations of system

There were a number of limitations with prototype 1 that were overcome with prototype 2. However, some still persisted despite the use of a dedicated PC running LINUX with no other peripherals to make demands on the system overhead. These issues generally related to the transfer of data between the PIC and its measuring devices (draw-wire sensors, Accelerometers) and the PC which controlled the audio-visual interface. The sensors, their I^2C bus, PIC and its communications bus (USB2) were capable of considerably greater speed than the PC could accommodate in real-time. Hence, some of the graphics occasionally appeared to judder or temporarily lost continuity. The decision was made to preserve the integrity of the recorded data at a minor cost to the graphical interface.

8.13.3 Production Costs

The hardware comprises two distinct types of component as noted in Table 8-2 and Table 8-3. These costs are estimates based upon manufacturing a batch of 1000 units in a general assembly workshop. Significant cost reductions can be realised for larger scale manufacturing using bespoke facilities.

Table 8-2 Estimated Costs for Hardware

Component (1 off unless otherwise stated)	Cost (£)	Bought-in or Manufactured
UHMWPE playing surface	35	Manufactured
Supporting board – particle board	20	Manufactured
Non-slip feet	5	Manufactured
Skate base	5	Manufactured
Accelerometer housing	10	Manufactured
Skate table and handle	25	Manufactured
Thrust bearing	5	Bought in
Ball catches (5 off)	5	Bought in
Bearings (4 off)	10	Bought in
Bearing housings (4 off)	10	Manufactured
Nuts, bolts, washers	10	Bought in
Sub-total	**140**	

There are two basic sensors, draw-wire and tri-axis accelerometer, and connecting electronics to link these to the main controller. These form the dominant manufacturing cost for the device.

Table 8-3 Estimated Costs for Sensors and Communication Electronics

Component (1off unless otherwise stated)	Cost (£)	Bought-in or Manufactured
Draw-wire sensors (4 off)	450	Bought-in
Tri-axis accelerometer board	50	Bought-in
I^2C communications board (2 off)	25	Bought-in
Master Control Board	100	Manufactured
Connectors and cable (4 off)	25	Bought-in
Sub-total	**650**	

The total anticipated costs are summarised in Table 8-4 which is similar to that developed in section 4.4 for prototype 1. It can be seen that the unit cost is anticipated to increase substantially although functionality and reliability are significantly enhanced for this

investment. The additional cost is dominated by the draw-wire sensors which are commercial grade devices and might be simplified for mass manufacture. Domestic devices will benefit from reduced development cost and potentially cheaper sensors making the target manufactured cost of £1000 per unit achievable.

A clinical device will require additional features or safe-guards as well as enhanced quality for greater reliability and longevity. Based upon similar domestic-to-commercial product conversions, such modifications are anticipated to raise the above total to a target manufacturing cost of £3000 for a commercial product. In medical equipment terms this not expensive and should therefore be accessible for most clinics and hospital and might even be used as a portable assessment unit.

Table 8-4 Prototype 2 - Anticipated Production Costs (1000 units)

Element	**Cost (£)**	**Remarks**
PC or Laptop	300	Basic specification, no additional software
Software	300	Linux OS plus development and maintenance costs
Hardware	140	See Table 8-2
Sensors, Comms, etc	650	See Table 8-3
Miscellaneous	100	Wiring, fixings and packaging
TOTAL	**1490**	Manufacturing for complete system

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