Recovery from Resistance Exercise in Later Life; Why Does it Matter, What Do We Know About it, and Can We Do Anything About it?

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Abstract

Resistance exercise is highly recommended for the maintenance of muscle mass and strength in older adults. Performing unaccustomed resistance exercise often leads to temporary reductions in physical functioning and sensations of muscle soreness in the days following the exercise bout. Optimising the recovery process after such exercise bouts is an important aim to maximise adaptation and limit side-effects, but the exercise recovery process in older adults is not well understood. Certain whole foods, such as cow's milk, have previously been suggested as effective recovery aids in this population but evidence for this is limited. Therefore, this thesis aimed to systematically map the current literature surrounding exercise recovery in older adults and identify suitable whole food interventions to aid recovery, alongside investigating older adults' knowledge and attitudes towards resistance exercise, exercise recovery, and exercise recovery strategies.

Chapter 3 presents a summary of the current literature following a systematic literature search and determines that there is limited research assessing recovery from resistance exercise in older adults, particularly in older women, and that literature in this area is inconsistent in both study protocol and findings. Chapter 4 details the results of a large-scale online survey, that show that there is a need to educate older adults on the benefits of resistance exercise, and the process of exercise recovery, in order to improve uptake and adherence to resistance exercise programmes. It also discusses older adults' lack of knowledge surrounding exercise recovery strategies, and their preference for whole food strategies over supplements. Lastly, Chapter 5 aimed to examine the effectiveness of a whole food product, cow's milk, for aiding exercise recovery in older adults. Due to difficult recruitment, the study was not adequately powered to detect any effect of condition. Various methodological considerations are presented for future research surrounding exercise recovery in older adults, including the suitability (or lack thereof) of traditional indirect markers of exercise-induced muscle damage.

In conclusion, the findings of this thesis demonstrate that the literature describing exercise recovery in older adults is lacking in strength and coherence. This thesis provides novel insights in to the knowledge and views of older adults of the exercise recovery process, and provides initial evidence-based recommendations for the progression of methodological approaches within this area of research.

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Preface

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List of Abbreviations

Activities of Daily Living	**ADLs**
Analysis of Variance	**ANOVA**
Creatine Kinase	**CK**
Centre of Pressure	**COP**
Cyclooxygenase	**COX**
Delayed Onset Muscle Soreness	**DOMS**
Exercise Induced Muscle Damage	**EIMD**
Effect Size	**ES**
Fat Free Mass	**FFM**
Gastrointestinal	**GI**
Hazard Ratio	**HR**
Interleukin	**IL**
Lactate Dehydrogenase	**LDH**
Myoglobin	**Mb**
Maximal Isometric Voluntary Contraction	**MIVC**
Muscle Protein Breakdown	**MPB**
Muscle Protein Synthesis	**MPS**
Maximal Voluntary Contraction	**MVC**
Non-Steroidal Anti-Inflammatory Drug	**NSAID**
Physical Activity Readiness Questionnaire	**PARQ**
Preferred Reporting Items for Systematic Reviews and Meta-Analyses	**PRISMA**
Polyunsaturated Fatty Acids	**PUFA**
Rating of Perceived Exertion	**RPE**
Total Quality of Recovery	**TQR**
Visual Analogue Scale	**VAS**
One-Repetition Maximum	**1-RM**

Chapter 1 : General Introduction and Literature Review

1.1. General Introduction

This literature review will seek to explain the importance of adhering to a resistance exercise programme for healthy ageing and will introduce concepts of exercise-induced muscle damage, adaptation, and exercise recovery. These concepts will be applied to older adults and various special considerations for this population will be discussed throughout. Towards the end of this review, various nutritional strategies for improving exercise recovery will be examined, with a particular focus on protein-rich whole foods - specifically cow's milk. The chapter will conclude with a summary of the literature and an outline of the experimental aims of this thesis.

1.2 Ageing and Older Adults

Ageing is defined as the process of growing old (Lea & Bradbery, 2020), and can be characterised by declines in function and an increased susceptibility to disease, frailty, or disability. Although often thought of as purely chronological, ageing refers to the biological decline in tissue or organismal function and is not necessarily linearly related to the time elapsed since birth (Jazwinski & Kim, 2019). When discussing ageing it is therefore sensible to be conscious that those of similar chronological ages may not present the same biological age. Despite this, for the purposes of this thesis we have set a minimum limit for what is considered to be an 'older adult'. Within the United Kingdom (UK), the National Health Service (NHS) classifies older adults as those aged 65 years and over, with their physical activity guidelines reflecting this classification (National Health Service, 2021; UK Chief Medical Officers, 2019). Hence, for the remainder of this thesis, 'older adults' are considered to be adults over 65 years old.

1.2.1 Demographics

The proportion of older adults within the general population of the UK is growing rapidly. As of 2021, there were approximately 12.5 million people aged 65 and over living within the UK (Office for National Statistics, 2021), with this figure expected to almost double to 20.6 million by 2068 (Office for National Statistics, 2018d). More imminently, it is estimated that by 2030, roughly one fifth of the population will be aged 65 or over (Office for National Statistics, 2017). This is due, in part, to decreases in mortality rates, and increases in life expectancy since the 19th century (Office for National Statistics, 2018a).

Although increases in life expectancy have now slowed (Office for National Statistics, 2018c), as of 2020 those currently aged 65 have an average life expectancy of 83.5 years for males, and 86 years for females (Office for National Statistics, 2020). Unfortunately, the increase in healthy life expectancy, and the number of years an individual can expect to live disability free, has not risen at the same rate as life expectancy and hence, there is now a greater proportion of older adults spending time in poor health (Office for National Statistics, 2018e). Given that age is a prominent risk factor for many diseases and debilitating health conditions including sarcopenia, cardiovascular disease, arthritis, and dementia, our ageing population represents an imminent major public health concern. Understanding the variables associated with optimising healthy ageing and developing successful public health interventions for extending healthy lifespan is therefore crucial in the coming years.

1.3 Skeletal Muscle Anatomy, Function, and Regulation

1.3.1 Anatomy and Importance of Skeletal Muscle in Health and Disease

The musculoskeletal system is essential for maintaining independence and health (Woolf et al., 2017). It is comprised of the skeletal muscles, bones, ligaments, tendons, cartilage, and other connective tissues (Boros & Freemont, 2017). As a whole, the system is responsible for enabling movement, protecting internal organs, supporting the body, participating in humoral signalling, and acting as a store for organic and inorganic molecules (e.g., carbohydrates, fats, calcium, phosphate) (Boros & Freemont, 2017). Additionally, the musculoskeletal system is also essential for maintaining optimal metabolic health, and is the primary site for insulin-stimulated glucose uptake alongside fatty acid metabolism and glycogen synthesis (Stump et al., 2006).

Skeletal muscle itself is any muscle that is connected to the skeleton to form a part of the mechanical system that moves limbs and other body parts. The body contains more than 500 skeletal muscles, accounting for up to 40 % of total body weight, and are made of specialised contractile tissue that can be controlled voluntarily by the nervous system (Tieland et al., 2018). Simplistically, muscles consist of bundles of muscle fibres (also known as myofibres or muscle cells), each containing small repeating functional units called sarcomeres (Figure 1.1). These sarcomeres are made from myofilaments (proteins), most commonly actin and myosin, and are responsible for the contraction and relaxation of the muscle through a process known as excitation-contraction coupling (Sandow, 1952) and the Sliding Filament Theory (Huxley & Niedergerke, 1954; Huxley & Hanson, 1954).

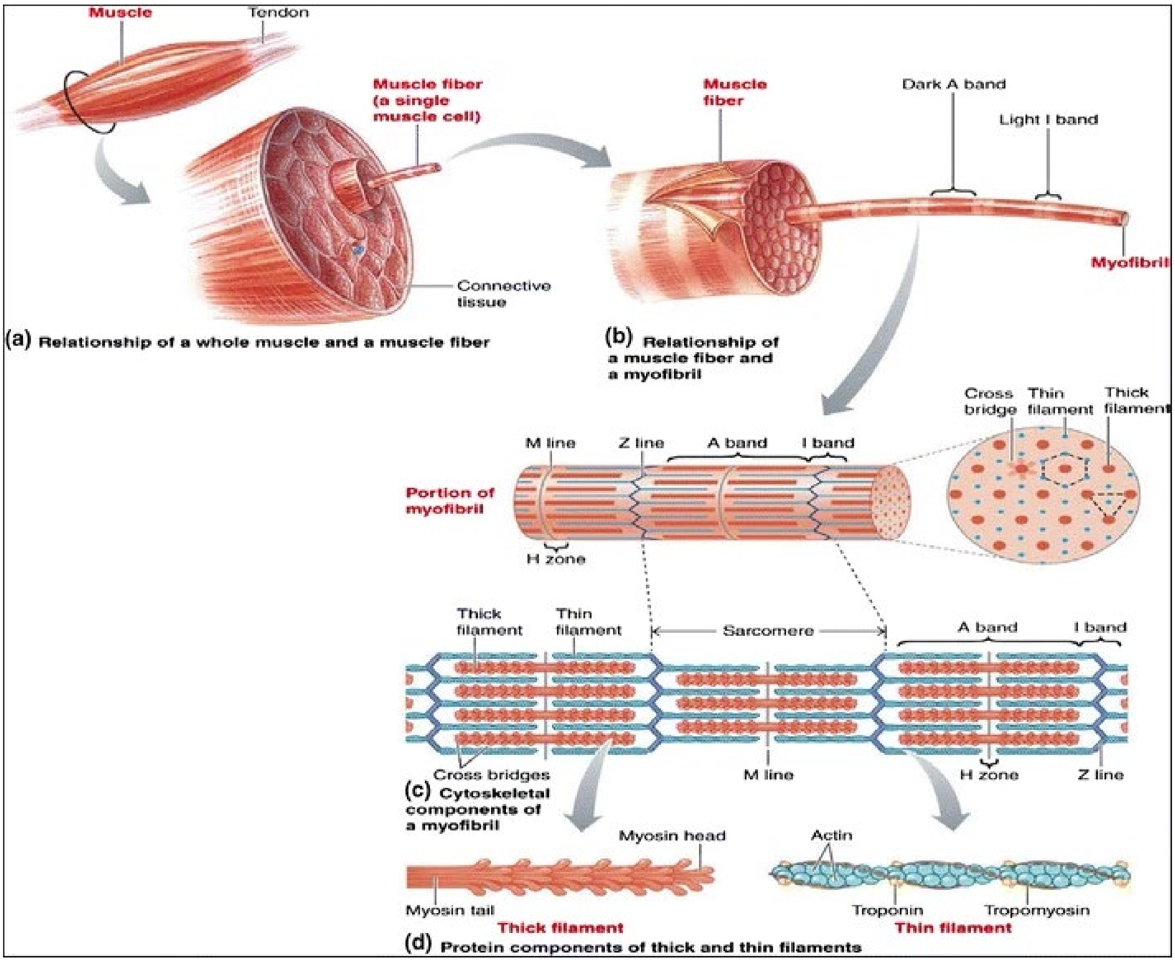

Figure 1.1 Structure of skeletal muscle (From: Sherwood, 2010; Frontera and Ochala, 2015)

1.3.2 Regulation of Skeletal Muscle

Like other tissues in the body, skeletal muscle undergoes constant cellular turnover. This process of muscle turnover allows for the elimination and replacement of proteins that have been functionally or structurally altered in order to maintain muscle function or adapt to stimuli (Andreu & Schwartz, 1995). The resultant skeletal muscle mass is dependent on protein turnover, i.e. the net balance between muscle protein synthesis (MPS) and muscle protein breakdown (MPB) within the muscle fibres (Schiaffino et al., 2013). For example, if the rate of MPS is greater than the rate of MPB, a net gain in muscle mass will occur during that period. Likewise, large quantities of muscle mass can be lost when MPB rates outweigh MPS over prolonged periods of time.

There are several factors that can alter net protein balance, but exercise and feeding are deemed the most potent stimuli (Burd et al., 2009). Generally, without a stimuli for MPS, skeletal muscle tissue exists in a state of negative net protein balance. This is predominantly because in fasted conditions, amino acids are released from skeletal muscle tissue for the remodelling of other tissues and to maintain glucose homeostasis. Feeding stimulates MPS, but this increase is transient, and alone it is not of sufficient magnitude to cause muscle protein accretion. Similarly, exercise alone cannot increase the net protein balance sufficiently to cause gains in muscle proteins (Figure 1.2). To induce substantial increases in net protein balance it is recommended that exercise is performed concurrently with feeding, or favourably, with protein feeding (Burd et al., 2009; Poortmans et al., 2012; Pennings et al., 2011). A more detailed mechanistic view of how exercise and protein feeding contributes to muscle remodelling will be discussed in Section 1.6.

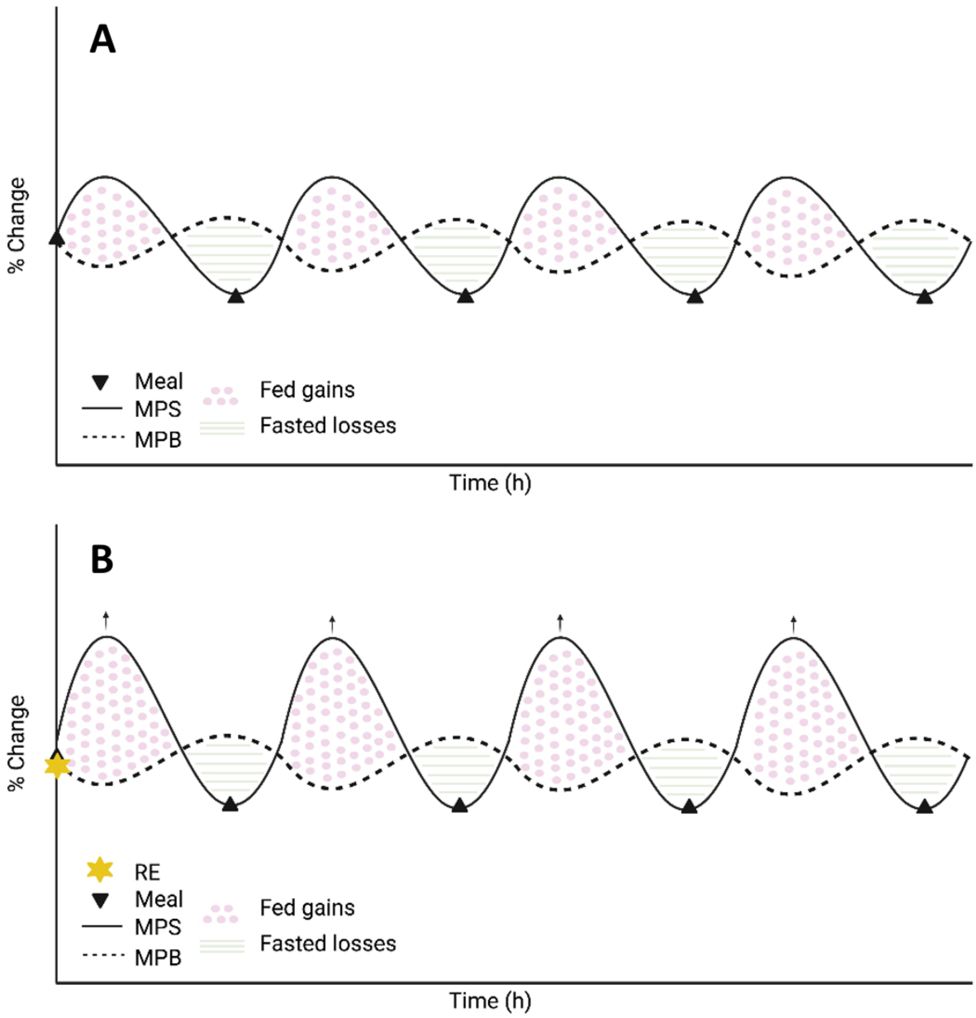

Figure 1.2 The difference in net protein balance after feeding (A) and after feeding with exercise (B). (Adapted from: Burd et al., 2009). MPS muscle protein synthesis, MPB muscle protein breakdown, RE resistance exercise.

1.4 Ageing and Skeletal Muscle

There are many changes that occur within the muscle with advancing age. Whilst not inevitable or universal, muscle weakness and atrophy are one of the most common characteristics of ageing muscle (Gallagher et al., 1997). Small declines are often seen in skeletal muscle mass and strength from the age of 30, with accelerated loss beginning at age 60 (Volpi et al., 2004; Boros & Freemont, 2017) (normative values for hand-grip strength over the lifespan, a robust marker of healthy ageing and of overall muscle strength, can be found in Figure 1.3 (Dodds et al., 2014)). This loss can be moderated to some extent by physical activity and diet (Phillips et al., 1997; Volpi et al., 2003; Wroblewski et al., 2011).

The reasons for these changes are thought to be complicated and multi-factorial, and the mechanisms underlying this are not yet fully elucidated. It has been proposed that these changes are mainly due to a disturbance in the homeostasis of muscle protein turnover coined 'anabolic resistance', but the extent of this effect is not completely understood (Cruz-Jentoft & Sayer, 2019; Burd et al., 2011). This being said, reductions in skeletal muscle mass can be explained at a cellular level by a reduced number and size of myofibres. This loss disproportionally affects type II muscle fibres which are primarily responsible for strength and power, and hence, reductions in muscle strength can exceed what is expected from the volume of muscle lost. The basis of this preferential loss over type I fibres is unclear, but it could be due to a decreased number of type II fibre satellite cells, however, this is likely not the only cause (Verdijk et al., 2007; Ciciliot et al., 2013). Further age-related disturbances to muscle quality and function may arise from a large variety of factors. This includes changes to the neuromuscular system, an intramuscular infiltration of fat and fibrosis, changes in hormones and growth factors, dysregulated protein degradation, dysregulated autophagy, increased oxidative stress and inflammation, mitochondrial dysfunction, cellular senescence, and epigenetic changes (Cruz-Jentoft & Sayer, 2019; Dhillon & Hasni, 2017; Padilla et al., 2021; Boros & Freemont, 2017; Frontera & Ochala, 2015; McCormick & Vasilaki, 2018).

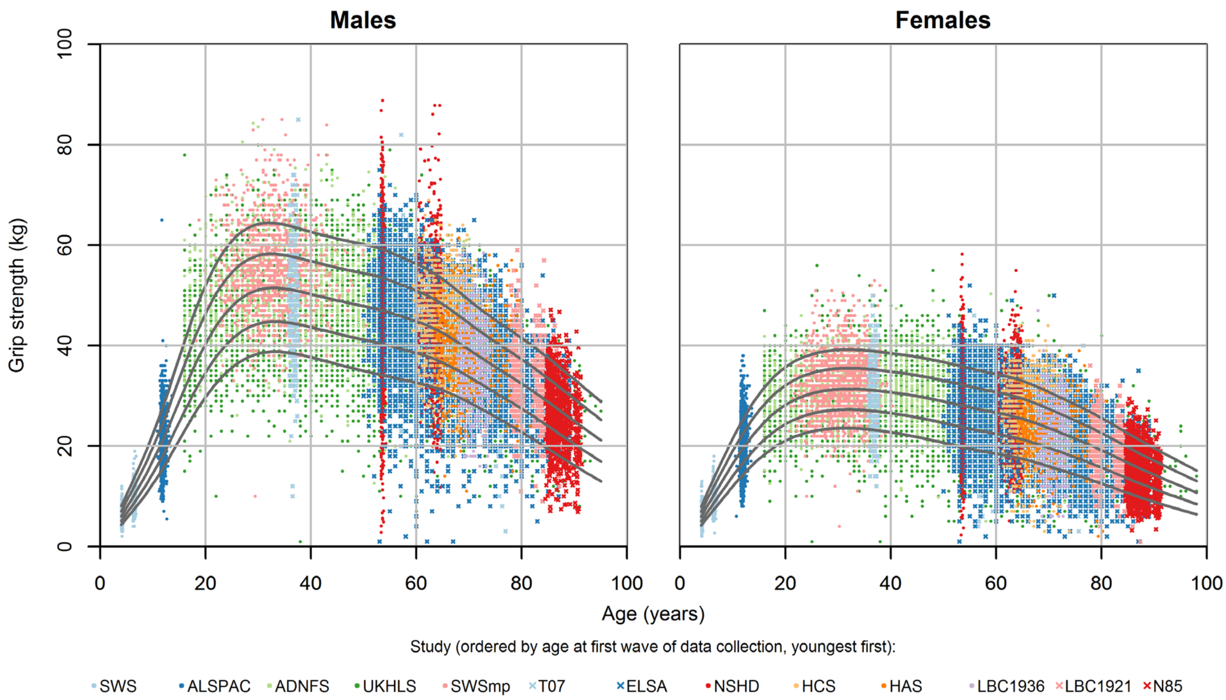

Figure 1.3 Normative data for grip strength across the life-course (From: Dodds et al., 2014)

1.4.1 Sarcopenia

Recently, sarcopenia has been defined as 'a progressive and generalised skeletal muscle disorder involving the accelerated loss of muscle mass and function' (Cruz-Jentoft et al., 2019), and it is now recognised as an independent condition as of 2016 with an International Classification of Diseases-10 (ICD-10) Code (Anker et al., 2016). Sarcopenia can have a debilitating effect on the individual but may also have a broader impact on family members and/or the social care system as a result of loss of independence (Pinedo-Villanueva et al., 2019). If left untreated, patients generally experience an increased incidence of falls (Bischoff-Ferrari et al., 2015; Schaap et al., 2017), disability (Malmstrom et al., 2016) and a decreased quality of life (Beaudart et al., 2017) that may ultimately lead to a loss of independence and require the need for long-term care (dos Santos et al., 2017). Sarcopenia has also been associated with increased mortality, indeed, using data from 197 individuals from the Aging and Longevity study, it was estimated that patients with sarcopenia had a significantly increased risk of all-cause mortality compared with non-sarcopenic individuals (HR: 2.32)(Landi et al., 2013). This is supported by a more recent meta-analyses, where diagnosis of sarcopenia using the EWGSOP2 criteria showed an increased risk of mortality (HR: 1.76) (Westbury et al., 2023). Additional evidence suggests that sarcopenia may also be associated with cardiovascular disease, respiratory disease, diabetes mellitus, and cognitive impairment (Bahat & Ilhan, 2016; Bone et al., 2017; Chang et al., 2016). In a recent meta-analyses, sarcopenia was shown to be independently associated with impaired cognitive function using data from 5994 participants (HR: 2.25)(Chang et al., 2016). The extent to which an individual will experience these negative consequences is thought to be dependent upon progression of the condition, and on existing comorbidities.

Recently, the European Working Group on Sarcopenia in Older People (EWGSOP2) proposed a comprehensive step-wise approach for the diagnosis of sarcopenia, focussing on low muscle strength as a key characteristic (Cruz-Jentoft et al., 2019). This updated approach suggests sarcopenia should be diagnosed in the presence of low muscle quality and quantity, and uses poor physical performance as an indicator of severe sarcopenia. The new approach also identified cut-off points for the measurements of variables that identify and characterise sarcopenia such as grip strength falling below 27 kg (men) or 16 kg (women), a low appendicular lean mass <7 kg/m^2 (men) or <5.5 kg/m^2 (women), a gait speed < 0.8 m/s and a Timed Up and Go (TUG) test time of >20 s. It is estimated that sarcopenia is present in 10-40 % of community-dwelling older adults, up to 56 % of hospitalized patients (Makizako et al., 2019; Mayhew et al., 2019), and from 18-73 % in long-term care home residents (Rodríguez-Rejón et al., 2019).

A number of lifestyle factors across the lifespan are also thought to contribute to the development of sarcopenia. Such risk factors include low levels of physical activity, the presence of chronic conditions or multimorbidity, and a poor quality diet low in protein and/or energy (Cruz-Jentoft & Sayer, 2019; Hurst et al., 2021; Scott et al., 2021). Many of these factors can be considered bi-directional and cyclical. For example, low levels of physical activity are thought to be a major determinant for the acceleration of losses in muscle mass and strength. Due to this decrease in lean mass and the resultant impairments to physical function, the drive and ability to eat can also reduce, leading to poor quality diets low in protein or energy, which further impacts losses in muscle strength and mass (Landi et al., 2016). A similar relationship also exists between physical activity levels, sarcopenia, and falls. After a fall, an individual can be immobilised due to injury or fracture, or the fear of falling again can prevent them from continuing their usual physical activity (Lord et al., 2001; Jehu et al., 2021). Again, this reduced physical activity accelerates losses in function and further increases falls risk, and so the cycle repeats. Whilst a sedentary lifestyle is thought to be the principal risk factor for sarcopenia, it should be noted that even the most physically active older adults, including endurance runners and weightlifters, still experience gradual declines in muscular strength and muscle fibre number from approximately 50 years of age (Faulkner et al., 2007). This illustrates that although physical activity is important in maintaining functional capacity, the pathophysiology of sarcopenia is both complex and multi-factorial.

1.4.2 Importance of Retaining Functional Capacity

Functional capacity is defined as the capability of performing tasks and activities that people find necessary or desirable in their lives (Guralnik et al., 1995). Retaining functional capacity is essential to living independently and enjoying a socially rich lifestyle in older age (da Silva et al., 2018; Guralnik et al., 1995). However, a continued loss of muscle mass and strength can result in impairments of an individual to perform their activities of daily living, and places them at an increased risk of falls, frailty, sarcopenia, and mortality (Hairi et al., 2010; Bischoff-Ferrari et al., 2015; Landi et al., 2013).

As early as the 1990s several research papers were published that described the relationship between reduced muscle function and a higher risk of future disability. In 1996, physical disability was defined as i) "the need for help with personal care such as eating, bathing, dressing or getting around at home" and/or ii) "the need for help in handling routine needs such as everyday household chores, shopping, doing necessary business or getting around for other purposes" (National Center for Health Statistics, 1996). A key study conducted in community dwelling older adults (>70 years) found that those with the lowest scores on a physical performance battery were four times as likely to have a disability four years later, even after accounting for age, sex, and the presence of chronic disease (Guralnik et al., 1995). As the main drivers for quality of life in older adults are sufficient energy, freedom from pain, ability to do activities of daily living, and ability to move around (Molzahn et al., 2010; Cevei et al., 2020), it is therefore unsurprising that a low functional capacity has also been linked with lower quality of life scores (Rizzoli et al., 2013).

The effects of muscle weakness on an older individual can be isolating and debilitating but can also present a material risk to mobility and life. Currently, falls are a leading cause of morbidity and mortality in older adults, with approximately a third of adults experiencing a fall each year (Tromp et al., 2001; Gribbin et al., 2009; Tinetti & Williams, 1997), and it is estimated that weakness in the lower extremities is the most prominent risk factor for falls (Lord et al., 2003; Pijnappels et al., 2008). Often, falls can result in serious complications to the individual including fractures, long hospital stays, loss of mobility, the need for residential care, and death (Tinetti & Williams, 1997; Sterling et al., 2001; Gribbin et al., 2009; Ayoung-

Chee et al., 2014). In the UK in 2017 there were 220,160 hospital admission for falls in patients aged 65 years and above (Office for Health Improvement and Disparities, 2022). When these falls occur in adults with frailty, their risk of hospital admission and death are robustly increased (Ensrud et al., 2007, 2009). Sadly, in the same year, 5,048 people aged 65+ died from having a fall, equating to 14 people every day (Office for National Statistics, 2018b). Not all falls lead to hospital admission but unfortunately, after a fall, the fear of falling can lead to more inactivity, loss of strength, and loss of confidence, which leads to a greater risk of further falls (National Health Service, 2022; Jehu et al., 2021).

Falls risk is often associated with age (Sterling et al., 2001), but a higher risk of falling is now increasingly accepted as a complication of sarcopenia (Fielding et al., 2011; Cruz-Jentoft et al., 2010), and is thought to be a result of changes in postural balance due to low muscle mass and strength (Gadelha, Neri, et al., 2018). Indeed, it has recently been demonstrated that an increase in the severity of sarcopenia may be associated with an increased risk of falling. By classifying the severity of sarcopenia present in 246 women into four stages, Gadelha and colleagues demonstrated an increased proportion of fallers from 15.4 % of women who were pre-sarcopenic, to 72.0 % of those considered to have severe sarcopenia (Gadelha, Vainshelboim, et al., 2018). Perhaps somewhat dependent on falls risk, fracture risk has also been shown to increase in sarcopenic individuals. In a systematic review from Cooper and colleagues in 2011 (Cooper et al., 2011), seven out of nine of the papers identified as assessing grip strength and fracture risk showed a clear association. Expressly, a lower grip strength was thought to increase fracture risk.

Decreased functional capacity has, unfortunately, also been associated with a general increase in mortality risk in several studies (Newman et al., 2006; Landi et al., 2013). After accounting for potential confounders (e.g. demographics, BMI, physical activity levels, smoking, cardiovascular disease), an observational cohort study found that mortality was higher in older people with lower physical capability. Specifically, 3075 community dwelling adults (aged 70-79 years) from the Health ABC (Aging Body Composition) study were asked to complete a 400-m corridor walk test, the results of which were compared with mortality after five years. For those able to complete the test, each additional minute taken to complete the test was associated with an increased hazard ratio (HR) of 1.29 for mortality. When comparing those with the poorest functional capacity to those with the best functional capacity, those with the poorest functional capacity were approximately three times as likely (HR = 3.23) to die during the five year period (Newman et al., 2006). In a similar study, Landi and colleagues assessed mortality risk in 80-85 year olds over a seven year-period. Individuals with a lower functional capacity had a higher risk of death than their healthy counterparts (HR = 2.32) after adjusting for potential confounders including age, gender, chronic diseases and activities of daily living impairment (Landi et al., 2013). Whilst mortality is undoubtedly an important outcome, it should be highlighted that the two studies described also found lower functional capacity to increase the risk of cardiovascular diseases, mobility limitation and physical disability and hence, provided evidence for a lower quality of life alongside diminished longevity.

There is no strong evidence that pharmacological approaches or nutritional interventions alone can successfully treat sarcopenia (Cruz-Jentoft & Sayer, 2019). Instead, current evidence based clinical practice guidelines suggest that physical activity, specifically resistance exercise, should be considered the primary treatment for sarcopenia (Dent et al., 2018; Moore et al., 2020).

1.4.3 Physical Activity and Exercise for Health and Ageing

As mentioned previously (see Section 1.3.2), physical activity is a key modulator for muscle protein turnover and skeletal muscle maintenance, but its benefits are also more widespread. Physical activity is deemed to be any bodily movement produced by the skeletal muscles that results in energy expenditure, whereas exercise is planned, structured, and repetitive with the aim of improving or maintaining physical fitness (Caspersen et al., 1985). Regular exercise in all forms is associated with a reduced risk of a number of chronic diseases and long-term conditions, and has been identified as one of the key factors in promoting and enhancing overall, and health related, quality of life. More specifically, adaptations to exercise include improved cardiorespiratory function, body composition, glucose homeostasis, cognitive function, muscle strength, mobility, and mitochondrial function, as well as mitigating declines in muscle mass (Figure 1.4). Further benefits arise from improved mental health, improved bone health, and reduced obesity (Izquierdo et al., 2021).

To maintain optimal health, current guidelines suggest that older adults should aim to perform 150 minutes of moderate intensity or 75 minutes of vigorous intensity aerobic exercise every week, alongside performing muscle strengthening activities on at least two days per week (UK Chief Medical Officers, 2019). The guidelines also state that some physical activity is better than none, with even light exercise bringing health benefits compared with a sedentary lifestyle, and hence, older adults are encouraged to build gradually to these recommendations if they are currently unable to attain them.

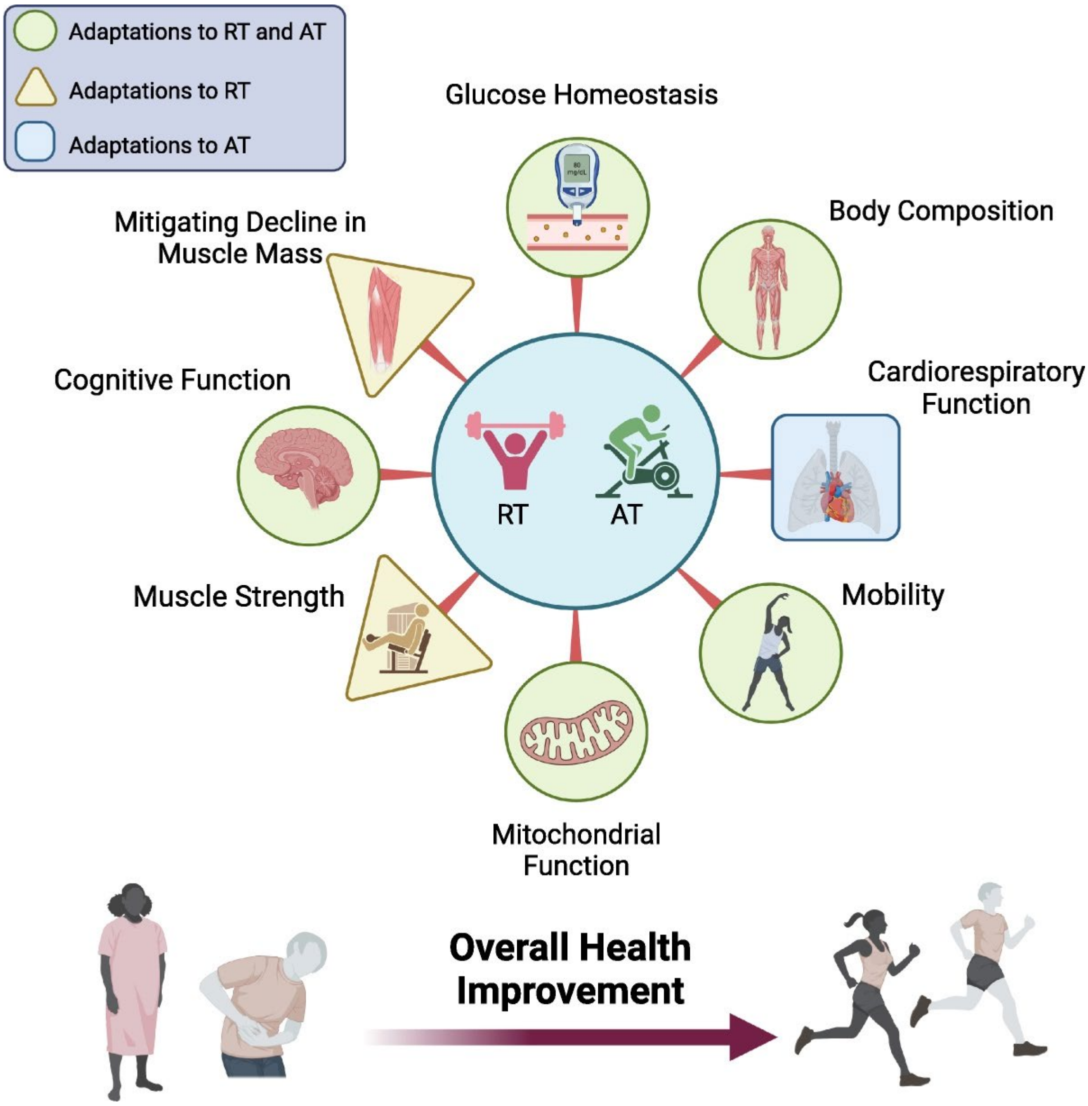

Figure 1.4 Adaptations to regular exercise. RT; resistance training, AT; aerobic training (From: Abou Sawan et al., 2023).

1.5 Resistance Exercise

1.5.1 Definitions

Resistance exercise, defined as 'any physical activity which produces skeletal muscle contraction/s by using an external resistance' (Dent et al., 2018) is a widely accepted and implemented form of exercise training. This may also be referred to as resistance training, weight-training, or weight-lifting. Training effects of resistance exercise are prominent across the neuromuscular system, and if performed regularly, resistance exercise can result in skeletal muscle hypertrophy, strength gains, and improved physical performance (Borde et al., 2015a). Examples of resistance exercise include lifting free-weights or dumbbells, using elastic therapy bands, or performing body-weight exercises such as press-ups. Traditionally, resistance exercise has been performed by younger athletes and active individuals to improve sporting or physical performance, but recently, a greater importance has been placed on participating in resistance exercise throughout the entire lifespan to improve health and quality of life (Cruz-Jentoft et al., 2014; Abou Sawan et al., 2023).

1.5.2 Importance of Resistance Exercise in Older Adults

There is now a large base of evidence that details the benefits of resistance exercise for healthy older adults, and for older adults with sarcopenia (Steib et al., 2010; Raymond et al., 2013; Borde et al., 2015a; Mende et al., 2022a; Grgic et al., 2020). Not only is resistance exercise recommended for maintaining general health in older adults (UK Chief Medical Officers, 2019), but current evidence based clinical practice guidelines now recommend that resistance exercise should be considered as a first-line treatment for the prevention and management of sarcopenia (Dent et al., 2018; Hurst et al., 2022).

One meta-analysis has reported that resistance exercise programmes can increase muscle strength by 13-90 %, and measures of muscle mass by 1-21 % (Borde et al., 2015a). This is mirrored in earlier reviews in 50-95 year olds who found similar increases in muscle strength and size of 24-33 % and 1.5-16 % respectively (Peterson et al., 2010; Stewart et al., 2014). Similar increases in muscle strength have also been found to be present in the oldest old (>80 years old)(Mende et al., 2022b). These gains in muscle strength may follow a dose-dependent manner, with increased training volume translating in to greater strength gains (Grgic et al., 2018). Muscle power, an important aspect of physical functioning, has also been shown to be improved by resistance exercise (Straight et al., 2016; Häkkinen et al., 2001)

These improvements in basic parameters of muscle function and morphology have also been shown to improve functional measures in older adults, such as balance and gait speed (Steib et al., 2010; Mende et al., 2022b). These increases in balance and muscle function can have a direct impact on falls risk. For example, an early study found that falls risk was decreased by 57.3 % in women aged 75-85 after completing a resistance exercise twice weekly for 25 weeks. The authors suggested this decrease was mediated by improvements in postural stability of up to 30.6 % as a result of the exercise programme (Liu-Ambrose et al., 2004). These findings are supported by several systematic reviews that have found strong evidence for resistance exercise having a positive effect on balance and falls risk in older adults (Seo et al., 2012; Keating et al., 2021). Gait speed, another risk factor for falls risk, has also been shown to be improved following resistance exercise, although this was almost exclusively concluded from straight-line walking tests (Keating et al., 2021). The authors of this review suggested that these conclusions could be made more assertively following multi-directional or double-task based scenarios.

Resistance exercise can also provide benefits outside of improving functional capacity and falls risk. Indeed, resistance exercise can play an important role in maintaining metabolic health with age. This is due, in part, to increases in muscle mass resulting in a greater volume of metabolically active tissue that can better regulate blood glucose, but also due to an increased insulin sensitivity (Yang et al., 2014). It has also been shown by recent meta-analyses that resistance exercise is effective in reducing fat mass in older adults, alongside an ability to lower haemoglobin A_{1c} and improve acute post-exercise lipid profiles (Lira et al., 2010; Lopez et al., 2022; Yang et al., 2014; Abou Sawan et al., 2023).

Ageing is associated not just with physical declines, but also cognitive impairments. However, evidence suggests that engaging in resistance exercise may improve age-related cognitive function and global cognitive function in healthy older adults, and older adults with mild cognitive impairments (Coelho-Junior et al., 2022; Landrigan et al., 2020). It is also possible that regularly participating in resistance exercise can decrease symptoms of depression and anxiety in older adults. This has been suggested to be a possible result of improved cognition, but other biological explanations include a reduced inflammatory status or direct effects from muscular contraction (Cunha et al., 2022). Other explanations for the improvements seen in mental health focus on social factors associated with resistance exercise simply as a result of the environment, such as providing social links, decreasing loneliness, and providing social support (Hart & Buck, 2019).

A recently published study demonstrates that a multitude of the aforementioned benefits of resistance exercise can be achieved after just a 12-week programme in healthy older women (Cunha et al., 2023). After performing three sessions of supervised, progressive resistance exercise a week for 12 weeks, significant improvements were observed as follows; increased muscular strength and skeletal muscle mass, decrease in total, relative, and regional body fat, increases in performance in measures of functional capacity, improvements in metabolic biomarkers (e.g. glucose, glycated haemoglobin, low-density lipoprotein cholesterol), improvements in cognitive performance, and decreases in depression and anxiety. This illustrates that even older adults that are deemed healthy, or not at risk of sarcopenia, are likely to still benefit from resistance exercise for their general health.

1.5.3 Training Guidelines

Current UK guidelines recommend that older adults try to participate in muscle strengthening exercises at least two times per week (UK Chief Medical Officers, 2019). However, as mentioned previously, even a little resistance exercise is better than none. Equally, well-trained older adults may feel motivated to perform more sessions per week.

Substantial research has been conducted in an attempt to identify the 'optimal' resistance training programme for older adults. There have been a number of studies investigating the optimal frequency for resistance exercise in older adults, often judging the effectiveness of training frequency by strength or mass gains (Steib et al., 2010; Borde et al., 2015b; Murlasits et al., 2012). This is a valid school of literature and provides important recommendations for the prescription of training frequency 2-3 times per week. According to a meta-regression of 25 studies, the resistance exercise programmes that were most effective for improving muscle strength in healthy older adults were characterised by a training intensity of 70–79 % one-repetition maximum (1-RM), a time under tension of 6.0 seconds per repetition, with a rest in between sets of one minute. It was also suggested that a training frequency of two sessions per week, with two to three sets per exercise, seven to nine repetitions per set, and a rest of 4 seconds between repetitions could also improve the efficacy of training (Borde et al., 2015b). A recent paper has also provided similar, but more specific guidance for resistance exercise prescription for older adults with sarcopenia (Hurst et al., 2022).

1.5.4 Promoting Resistance Exercise in Older Adults

Resistance exercise is not regularly performed by the majority of older adults. Indeed, it has been reported that just 29 % of older adults (75 +) are meeting the strength training recommendations set out in the UK's physical activity guidelines of performing strength training on two days every week (Sport England, 2022).

The general consensus within the literature is that there are several main barriers to older adults regularly participating in resistance exercise (Cavill & Foster, 2018). One umbrella review identified these barriers as time-constraints, a lack of access to suitable facilities, a lack of motivation, a lack of enjoyment, or misconceptions that resistance exercise is dangerous for older adults. A less common but still prevalent concern is the fear of looking 'too muscular' (Cavill & Foster, 2018). In the only specific review for barriers to older adults performing resistance exercise, Burton et al. identified additional barriers to resistance exercise that were not highlighted in the umbrella review such as poor health and a lack of social support (Burton et al., 2017).

A recent study proposed that the reason for the low uptake and adherence of resistance exercise in older adults was likely due to several factors; (1) being unaware of the physical activity guidelines and lacking knowledge of what constitutes strength training, (2) a lack of enjoyment of resistance exercise, (3) a lack of provision/ suitable facilities to perform resistance exercise for this age group, (4) misconceptions that older adults could not safely perform resistance exercise (Gluchowski et al., 2022). Before this, no study had yet actively sought to determine if older adults were aware of the physical activity guidelines surrounding resistance exercise, and so this may highlight the importance of education for improving uptake in an older population.

Motivators for resistance exercise have been researched alongside barriers to participation and are usually presented within the same papers. The main motivators for engaging in resistance exercise are commonly considered to be improvements in physical health such as building strength or losing weight, improvements in mental health, enjoying exercise, increased self-efficacy of using gym equipment, social interaction, and access to age-appropriate classes and facilities, but more specifically, access to good and comfortable facilities (Burton et al., 2017; Gluchowski et al., 2022; Cavill & Foster, 2018).

There is evidence to suggest that whilst older adults may initially be reluctant to engage with resistance exercise, getting individuals over the 'first hurdle' may be key to increasing participation amongst older adults. Previous studies have found that some older adults who had reservations about participating, often encountered a 'pleasant surprise' after familiarisation with the exercise, and adhered to resistance exercise long-term (Gluchowski et al., 2018; Foyster et al., 2022; Gluchowski et al., 2022). Hence, increasing adherence may follow naturally from increasing uptake. For this, it appears that providing better education on what resistance exercise entails and the benefits of it, alongside the facilities to perform it correctly should be considered important.

A popular model for promoting adherence to exercise programmes is the COM-B (Capability (C), Opportunity (O), Motivation (M)) model of behaviour change (B) (Michie et al., 2011). This model contains three essential conditions: capability, opportunity, and motivation, which are thought to both influence and be influenced by behaviour. Around these three essential conditions nine intervention functions aimed at addressing deficits in one or more of these conditions are positioned, and around this are placed seven categories of policy that could enable those interventions to occur (Figure 1.5). These constructs have been tested and validated for their ability to predict engagement in moderate-vigorous physical activity previously (Howlett et al., 2019). It is possible that applying this model to resistance exercise participation in older adults could increase participation, such as providing education (intervention function) or increasing service provision for older adults to participate (policy category).

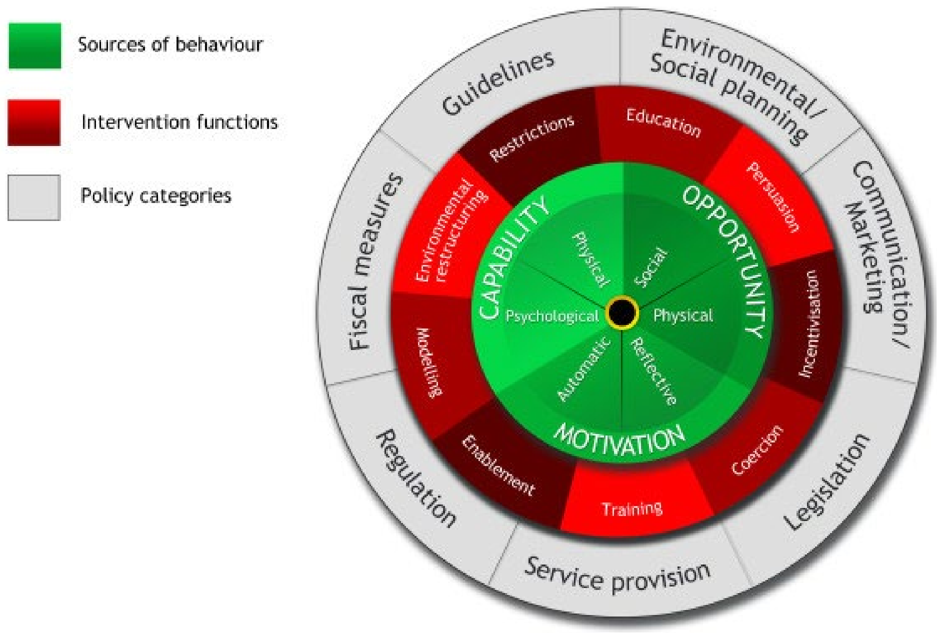

Figure 1.5 The COM-B model of behaviour change (From: Michie, van Stralen and West, 2011)

1.6 Physiology of Resistance Exercise Adaptation in Skeletal Muscle

To understand how any adaptation to exercise occurs, we must explore the physiological effects of a single bout of exercise and then understand how this accumulates into a phenotypic or functional change with chronic training. In this section (1.6), adaptation to a single bout of resistance exercise will be discussed first, followed by an examination of how this translates to functional changes over time.

1.6.1 Response to a Singular Bout of Resistance Exercise

The adaptation response to a bout of resistance exercise is a highly orchestrated process that is characterised by a predictable pattern of cellular processes aimed at removing damaged muscle, and replacing it with new muscle tissue. The process of muscle remodelling may be split in to several stages; mild structural damage, degradation and inflammation, and regeneration and growth.

Resistance exercise typically involves performing high-force muscle actions, both concentrically and eccentrically. These muscle actions can result in muscle damage - a simplification used to denote a breadth of structural, molecular, metabolic, and functional perturbations after unaccustomed exercise. Primary structural muscle damage is a result of mechanical loading of the muscle during eccentric contractions (Proske & Morgan, 2001; Tee et al., 2007). It has been proposed that during lengthening contractions, sarcomeres are forcefully lengthened to beyond myofilament overlap, causing sarcomeres to ‘pop’, and tension to increase on passive structures - resulting in the deformation of non-contractile proteins. Continued repetitions of such contractions leads to further fibre degradation and ultrastructural damage (Proske & Allen, 2005). Secondary muscle damage can also occur from uncontrolled movement of Ca2+ in to the cytoplasm, which activates Ca2+-dependent proteolytic and phospholipase A2 pathways that degrade damaged structural proteins (Gissel, 2005).

The activation of Ca2+ dependent proteolytic pathways signals a pro-inflammatory cytokine release, but the degradation of damaged myofibrils can also be mediated by other, non-inflammatory, biological pathways such as the ubiquitin-proteosome pathway. The inflammatory response that follows is vital for clearing damaged tissue and initiating repair in a highly organised and temporal manner. Almost all immune cell types are involved in this cascade, including neutrophils, macrophages, lymphocytes, eosinophils, and mast cells (Chazaud, 2016). Macrophages are the predominant leukocytes at every time-point following muscle damage and exert specific functions throughout the process of muscle remodelling. However, the first group of immune cells to infiltrate the muscle tissue is likely to be neutrophils which phagocytose damaged fibres and other cellular components, and may also be implicated in further aggravating existing damage in the muscle fibres due to their release of cytotoxic enzymes and reactive species (Hyldahl & Hubal, 2014; Nguyen & Tidball, 2003). Macrophages may also cause further damage on initial infiltration to the muscle tissue, releasing pro-inflammatory cytokines such as interleukin (IL)-1β and tumor-necrosis factor-α (TNF-α), and are associated with phagocytosis of the damaged muscle fibres (Chazaud, 2016). These macrophages later change their phenotype to become anti-inflammatory, releasing growth factors such as transforming growth factor β1 and IL-10, and IL-1. This allows for the resolution of inflammation, and the activation of myogenic precursors cells, or satellite cells, that are essential for muscle regeneration.

As discussed in Section 1.3.2 the skeletal muscle requires constant cellular turnover to eliminate and replace proteins that have been functionally or structurally altered in order to maintain muscle function or adapt to stimuli. Once the damaged proteins have been cleared, and the inflammation has been dampened, regeneration of key proteins and structures is required. These adaptations to resistance exercise are reliant on positive net muscle protein balance and the addition of satellite cells to pre-existing muscle fibres. Satellite cells, the main muscle stem cells, are activated by several factors throughout the muscle remodelling process (Fu et al., 2015). Once activated, these quiescent satellite cells proliferate rapidly, becoming myogenic precursor cells, known as myoblasts, before committing to terminal myogenic differentiation and fusing with pre-existing muscle fibres to rebuild and add functional units (Yin et al., 2013).

Both muscle protein breakdown and muscle protein synthesis are upregulated throughout the muscle remodelling process, but muscle hypertrophy as a result of successful regeneration of muscle fibres will only occur in the presence of a net positive protein balance (Baar & Esser, 1999; Burd & De Lisio, 2017; Moore et al., 2014). Singularly, both protein ingestion and resistance exercise will stimulate muscle protein synthesis, but synergistic effects of these stimuli will produce a much greater muscle protein synthetic response, and hence, repeated bouts of resistance exercise coupled with protein feedings will result in a greater increase in muscle mass and strength over time (Burd et al., 2019).

1.6.2 Adaptation to Chronic Resistance Exercise

Chronic resistance exercise produces distinct physiological changes through repeating the cycles of muscle damage and repair that were discussed in the previous section (1.6.1). If executed correctly, systematic training can improve an individual's muscular strength and general fitness as the body adapts to the physical load, as an organism would change to better survive new environmental challenges. The theory of supercompensation, or the general adaptation syndrome theory as it was later called by Dr Hans Selye (Selye, 1951; Bompa & Buzzichelli, 2018), is the underlying principle of any exercise training. It proposes that when an individual performs unaccustomed exercise, acute physiological responses occur that result in the accumulation of fatigue. These responses can include cardiovascular, metabolic, hormonal, and neuromuscular changes, and the magnitude of these changes is dependent on the type, intensity, and volume of the exercise (Bompa & Buzzichelli, 2018). Post-exercise, this accumulation of fatigue can result in reduced physical functioning that can last for several days before the body restores homeostasis. If sufficient time is allowed between training sessions, the body can establish a new, greater homeostatic level. In other words, their baseline functional capacity can increase. If repeated consistently, the body can continually shift this baseline functional capacity upwards, meaning muscle strength and function will increase. For a graphical visualisation of this theory see Figure 1.8.

1.6.3 Blunted Adaptation to Resistance Exercise in Older Adults

It is well known that resistance exercise improves functional capacity and muscle morphology in older adults, and that it does so through the same physiological pathways as those that allow adaptation in younger adults (Mende et al., 2022a). However, there is some evidence to suggest that these pathways may be altered or blunted by ageing, offering a challenge in the understanding of adaptation to resistance exercise in older adults.

One pathway that has received significant attention for its role in exercise adaptation and sarcopenia is the muscle protein synthetic response to protein consumption and resistance exercise. After seminal work in the early 2000's (Volpi et al., 2000; Cuthbertson et al., 2005), in 2015, a blunted response to protein feeding was observed amongst 40 older men (74 ± 1 years) when compared with 35 young men (22 ± 1 years) despite there being no significant differences in basal protein synthetic rates. The difference in post-prandial muscle protein synthetic rates between the age groups was reported to be as much as 16 % lower in the older group (Wall et al., 2015). Similarly, it has been suggested that older adults may need to consume a larger bolus of protein to maximally stimulate muscle protein synthesis. Indeed, it is estimated that whilst approximately 0.24 g·kg·BM of protein is sufficient to maximally stimulate muscle protein synthesis in younger adults, older adults could require up to 0.4 $g·kg^{-}·BM$ (Moore et al., 2014). It has also been shown that there is a blunted muscle protein synthetic response to resistance exercise. After performing eight sets of ten repetitions of knee extension at 70 % 1-RM, mixed muscle protein synthesis was elevated in both young (27 ± 2 years) and older (70 ± 2 years) adults, but were higher in young than old at all time points (Fry et al., 2011).

It is also possible that adaptation to resistance exercise may be hampered in older adults due to age-related decreases in satellite cell number and responsiveness (Nederveen et al., 2020; Snijders et al., 2014). Previous studies have demonstrated that increases in satellite cell content as a response to exercise are reduced in older compared with younger men, seeing only a 51 % increase 24-hours after a resistance exercise bout compared with a 141 % increase respectively (Dreyer et al., 2006). This could result in a reduced capacity to increase muscle mass with chronic training but is unlikely to affect the acute rate of recovery from resistance exercise (Karlsen et al., 2019). Furthermore, the macrophage response to resistance exercise may be dysregulated in older adults (Reidy et al., 2019). The precise effects and mechanisms of this dysregulation of the macrophage response to muscle damage is still unclear, but it could alter the recovery response to resistance exercise in older adults, either acutely or chronically (Jensen et al., 2020).

1.7 Exercise-Induced Muscle Damage and Exercise Recovery

Exercise-induced muscle damage (EIMD) is the term given to the temporary disturbance in the function and/or structure of skeletal muscles as a result of intense or unaccustomed exercise. It is considered to be a normal and integral part of the process of adaptation to resistance exercise. Exercise recovery, on the other hand, is the process of resolving these physiological disturbances. This process begins once exercise has ceased, and can be considered complete when physiological disturbances are returned to baseline and homeostasis is achieved. Literature reporting on EIMD and exercise recovery generally focusses on indirect markers of EIMD and the corresponding inflammatory response to determine the rate of exercise recovery and hence, these terms are often found adjacently. Little research has been conducted on EIMD in older adults and hence, Section 1.7.1 to 1.7.8 will focus on the current evidence base in younger adults, before this is applied to older adults in Section 1.7.9.

1.7.1 Physiology of EIMD

As mentioned previously, EIMD is a result of the structural muscle damage that occurs during unaccustomed exercise and the further degradation of these damaged proteins to allow for the repair and growth of muscle fibres (See Section 1.6.1 or Figure 1.6). EIMD is most commonly observed following an exercise bout during which high force eccentric muscle actions are performed. Primary muscle damage is often described as the ultrastructural damage to contractile proteins and skeletal muscle cell membranes that occur during exercise as a result of mechanical loading of the muscle (Proske & Morgan, 2001). Secondary muscle damage is the result of the inflammatory cascade intended to clear damaged tissue in the days following the exercise bout (Owens et al., 2019). This includes the infiltration of a number of immune cell types such as neutrophils, mast cells and eosinophils into the damaged muscle (Chazaud, 2016).

The recovery process from muscle damage is complex, multi-faceted and is affected by a number of variables, and the underlying reasons for individual variability are therefore poorly understood. It is currently thought that muscle satellite cell involvement and nutritional factors, such as protein intake, are major contributors to the process of exercise recovery (Owens et al., 2019).

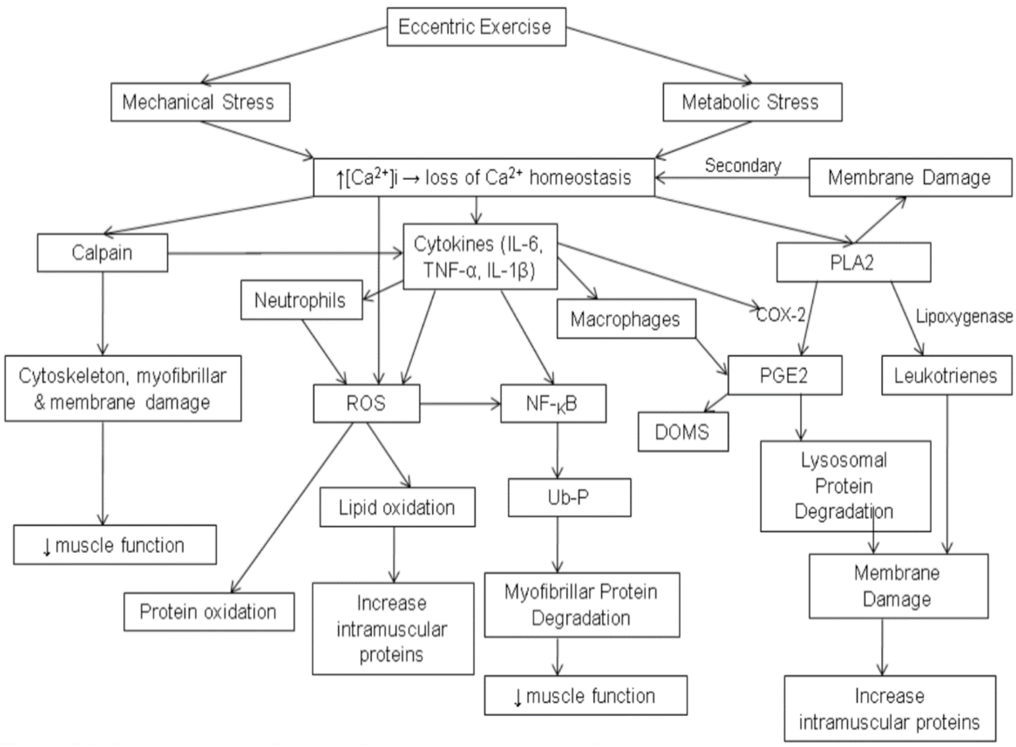

Figure 1.6 An overview of the postulated processes occurring during exercise induced muscle damage (From: Cockburn, 2010). COX-2 = cyclooxygenase-2, DOMS = delayed onset muscle soreness, IL-6 = interleukin-6, IL-1β = interleukin-1beta, NK-kB = nuclear factor kappa-light chain enhancer of activated B cells, PGE2 = prostaglandin

E2, PLA2 = phospholipase A2, ROS = reactive oxygen species, TNF- α = tumor necrosis factor-alpha, Ub-P = ubiquitin proteasome

1.7.2 Overview of Symptoms and EIMD Markers

EIMD may manifest as muscle soreness, inflammation, and decreases in skeletal muscle function and exercise capacity (Owens et al., 2019). These symptoms may appear immediately after exercise and can persist for up to two weeks (Figure 1.7). Importantly for exercise training purposes, these symptoms represent the damage and metabolic disturbance of skeletal muscle and hence, the resolution of these symptoms can indicate adaptation to exercise and a readiness to continue training (Fell & Williams, 2008).

The only method to directly measure the extent of muscle damage requires invasive methods, usually a muscle tissue biopsy that is later assessed via electron and/or light microscopy for structural changes to the muscle fibres. Most research groups therefore opt to utilise more indirect markers of muscle damage for both ethical and financial reasons. Generally, the most widely accepted indirect marker of muscle damage within the literature is the reduction of muscle strength and function which can see decreases anywhere from 10 % in concentric exercise protocols to 65 % following maximal eccentric exercise (Clarkson & Hubal, 2002). Comparably popular as a marker of muscle damage is the occurrence of delayed onset muscle soreness (DOMS), although the physiological underpinning of why DOMS occurs is still unclear (Yu et al., 2013). Typically, DOMS begins as early as 8 hours post-exercise, peaks at 24-48 hours and has usually subsided before 96 hours (Clarkson & Sayers, 1999). Both of these markers are extensively used as an instrument for assessing recovery rate in the days following intense exercise. Another common marker used within the exercise recovery research is the presence of muscle-specific proteins such as creatine kinase (CK) and myoglobin (Mb) within plasma. However, these proteins often peak approximately 2-6 days after exercise, showing a poor temporal relationship with changes in function or increases in soreness. These muscle-specific proteins are highly individual (Baird et al., 2012), and their usefulness for measuring the severity of muscle damage may therefore be limited to identifying the occurrence of damage. Given their role in the muscle remodelling process, the presence of inflammatory cells in blood samples and muscle tissue have also been used for confirming muscle damage, but much like muscle-specific proteins, they are likely limited to identifying that an inflammatory response has occurred rather than for assessing the magnitude of damage (Peake et al., 2016).

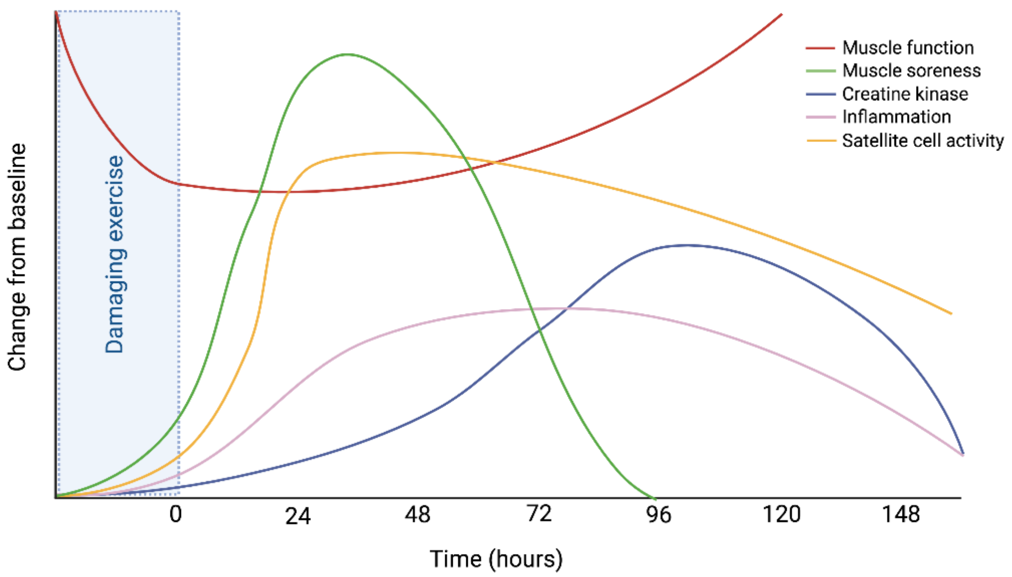

Figure 1.7 Time course of events following a bout of muscle damaging exercise

1.7.3 Muscle Function as a Marker of EIMD

Decrements in muscle function are often considered to be the most reliable marker of EIMD, and are extensively used within the literature (Damas et al., 2016; Stožer et al., 2020). The most common facet of muscle function for determining EIMD is muscular strength, as measured by either isometric or isotonic maximal voluntary contractions. The magnitude of strength loss and the subsequent rate of recovery is largely dependent on the severity of EIMD (Peake et al., 2016), but can see reductions of 20-50 % in moderate severity EIMD that usually recovers within seven days (Lauritzen *et al*., 2009; G. Paulsen *et al*., 2010). Mild cases of EIMD usually only see strength decrements smaller than 20 %, and are generally recovered within a 48-hour period (Crameri et al., 2007). These measures of muscular strength are usually obtained through the use of a linear dynamometer, but 1-RM strength testing can also be used.

Other components of muscle function can also be used as an indirect marker of EIMD. For example, muscular power and dynamic strength have previously been shown to be highly sensitive to muscle damage (Warren et al., 1999; Molina & Denadai, 2012; Raeder et al., 2016) and, like muscle strength, can also be measured using a dynamometer. However, dynamic strength production can also be measured by using task-specific methods, such as measuring vertical jump height or bench ball throw distance (Bartolomei et al., 2019; Byrne & Eston, 2002). These are both complex and multi-jointed tasks, and hence, assessments like these can be more applicable when assessing how performance is affected since they better represent sporting movements when compared with isometric muscle strength assessment. However, measuring jump height is likely to be unfeasible in populations such as older adults. Instead, population specific tasks are often used to assess their level of muscle function including stair ascent and descent, timed up-and-go (TUG) tests, chair stand tests, and balance tests.

A decrease in muscle strength can be observed immediately after eccentric exercise, but further strength losses can ensue 24-hours later as a result of mechanical damage and excitation-contraction coupling failure (Owens et al., 2019; Hyldahl & Hubal, 2014). Additional loss of strength over the 72-hour period post-exercise has been attributed to the inflammatory response to mechanical muscle damage, but may also be caused by central inhibition as a result of pain (Clarkson & Hubal, 2002; McKune et al., 2012). After 72-hours, it is likely that strength loss is largely caused by calpain-mediated protein degradation of the contractile proteins (Murphy et al., 2013).

1.7.4 Muscle Soreness as a Marker of EIMD

EIMD is associated with soreness of the used muscles following bouts of unaccustomed resistance exercise, and is commonly referred to as delayed onset muscle soreness (DOMS). Sensations of muscle soreness usually begin at 8-24 hours after exercise, peak at 24-48 hours post-exercise, and are resolved within 4-7 days (Damas et al., 2016). Muscle soreness may also be accompanied by muscle stiffness, sensitivity, and localised swelling (Clarkson, 1997). The most common method to assess DOMS is through the use of a self-administered visual analogue scale, usually anchored with statements corresponding to little or no pain on the left side of the scale, and statements of extreme pain to the right (Kersten et al., 2014). Another less widely used but less subjective method to assess DOMS (Fleckenstein et al., 2017) is through the use of pressure pain threshold assessment. This involves quantifiable pressure increasingly being applied to the affected muscles until the participant indicates discomfort, with the pressure being applied at this point being recorded.

Although the mechanisms that cause DOMS are not completely understood, there are various theories as to its origin. Currently, there are two main theories as to why an individual may experience DOMS. The first, is that the release and activation of B2-bradykinin receptors during exercise results in mechanical hyperalgesia (an exaggerated response to a painful mechanical stimulus) by upregulating nerve growth factor and sensitising nociceptors (Murase et al., 2010). The second suggests an upregulation of glial cell line-derived neurotrophic factor (GDNF) by cyclooxygenase (COX)-2 activation is a key driver for DOMS after exercise. This was evidenced by a complete suppression of DOMS development after eccentric exercise by the administration of COX-2 inhibitors (Murase et al., 2013).

The appearance and severity of DOMS does not appear to correlate well with any histological changes within the affected muscle (Nosaka et al., 2002). Indeed, DOMS does not directly correlate in magnitude or time-course with the inflammatory response, which is thought to be the main mechanism associated with DOMS (Peake et al., 2016). Additionally, the subjective nature of DOMS may cause large variation despite similar levels of structural damage and inflammation, and should therefore only be used alongside other indirect markers of EIMD to create a clearer overview. It is possible that DOMS may impact an individual's feelings of readiness to exercise and may decrease the likelihood of the individual performing further exercise or decrease the quality of the next training session. Hence, even if it cannot be used to directly quantify EIMD, it is important to measure and consider when designing training programmes (Malm, 2001).

1.7.5 Circulating Muscle Proteins as a Marker of EIMD

Following EIMD, intracellular muscle proteins can leak in to the extracellular space due to membrane damage. Numerous muscle proteins can then be found in the plasma, but the most commonly used muscle damage biomarkers are creatine kinase (CK), myoglobin (Mb), and lactate dehydrogenase (LDH)(Stožer et al., 2020). The most researched of these is CK due to having relatively larger plasma protein concentrations after EIMD, and the lower cost of the assay compared with other biomarkers (Sorichter et al., 1995). Generally, increases in the plasma concentration of muscle proteins begins 12-hours after exercise, and peaks four to six days later. At a basic level, plasma concentrations of muscle proteins are determined both by their rate of leakage from the muscle and their rate of removal from the plasma. However, the magnitude of this change is also dependent on a variety of factors, such as training status, exercise type, exercise intensity, and is also highly individual (Koch et al., 2014; Damas et al., 2016).

Although circulating muscle proteins are widely used as an indirect marker of EIMD, their large variability should be considered a major limitation. The normal range for baseline levels of CK can range from 20 up to 16,000 U/L in some cases, with similar variability seen in the increase as a result of exercise (Baird et al., 2012). Additionally, whilst it is not disputed that circulating muscle protein levels rise after exercise, they are yet to be directly correlated with structural muscle damage or with any other marker of EIMD.

1.7.6 Immune Cells and Cytokines as a Marker of EIMD

There is a strong inflammatory response to eccentric exercise that contributes to EIMD and is essential for adaptation to resistance exercise. This response is highly orchestrated and involves both immune cells and associated cytokines. Macrophages are immune cells found in skeletal muscle, and are quiescent until activated by muscle use or trauma (Tidball, 2017). Macrophages generally appear one day after neutrophil activation, and peak in activity 12-72 hours after, but can remain elevated for up to two weeks (Chazaud, 2016). However, the exact time course for inflammatory cell infiltration following resistance exercise is yet to be fully elucidated. Macrophage number and activity is usually assessed by obtaining a blood sample or a biopsy of the exercised muscle.

The most commonly assessed immune cells in the EIMD literature are macrophages, and can roughly be classified in to two categories; pro-inflammatory (M1) macrophages, and anti-inflammatory (M2) macrophages which are associated with anti-apoptosis and growth factors (Mosser & Edwards, 2008). The different classifications of macrophages can generally be attributed to either the degradation phase of EIMD (M1) with CD68+ macrophages appearing 12-48-h after exercise, or the tissue repair or growth phase (M2) with anti-inflammatory macrophages appearing in 3-7 days (Chazaud, 2016). Although there is some overlap between the two, the increase of anti-inflammatory markers is thought to inhibit the release of pro-inflammatory cytokines (Howard et al., 2020). However, recent research has suggested that there may be no purely pro- or anti- inflammatory macrophages, as the most commonly observed macrophage cell type after EIMD was positive for both anti- and pro-inflammatory macrophage markers (CD68, CD11b, and CD206)(Jensen et al., 2020).

During the pro-inflammatory phase cytokines such as IL-6, IL-1β, and TNF-α are secreted by M1 macrophages (Chazaud et al., 2003). M2 macrophages then secrete anti-inflammatory cytokines such as IL-10, alongside transforming growth factor-β1 and insulin-like growth factor-1 (Arnold et al., 2007; Peake et al., 2016). However, more than any other cytokine, IL-6 is released in large amounts after exercise, with some studies showing up to a 100-fold increase (Ostrowski et al., 1998; Pedersen et al., 2001). It is thought that IL-6 may be responsible for the acute phase response to exercise, with data showing a peak in IL-6 immediately after exercise and a rapid decline thereafter. Although also being released in the pro-inflammatory phase, IL-6 has mainly anti-inflammatory effects, and can inhibit the expression of pro-inflammatory cytokines TNF-α and IL-1 (Pedersen et al., 2001).

Although the inflammatory response to exercise is heavily studied, its direct application as a marker of muscle damage is still somewhat contentious. The accumulation of inflammatory cells in the muscle tissue is considered an important indicator of EIMD (Paulsen, Mikkelsen, Raastad, & Peake, 2012). However, it is possible that whilst studied as a means to understand the adaptive response to exercise it has throughout the years been adopted as a method to quantify the severity of muscle damage when in fact, the complexity of the inflammatory response makes it hard to draw parallels with histological damage. That being said, leukocyte accumulation in the muscle following damaging exercise has been shown to be associated with declines in muscle strength, but only when muscle damage is moderate or severe, and not when EIMD is mild (Malm *et al.*, 2004; Paulsen *et al.*, 2010; Peake *et al.*, 2016). There is limited evidence to suggest that the magnitude of cytokine expression is related to the extent of muscle damage (Peake et al., 2016). Indeed, although IL-6 is a major regulator of myogenesis, and has been reported in many papers alongside EIMD, it has other functions and also appears to be central in regulating hepatic glucose output (Pedersen et al., 2001), and it is likely a poor reflection of the state of muscle (dis)repair and rather, may be better as an indicator that strenuous exercise has taken place.

1.7.7 Satellite Cells as a Marker of EIMD

Satellite cells, otherwise known as the muscle stem cells, rapidly proliferate and differentiate once activated by exercise to support muscle regeneration and growth (Howard et al., 2020). Although not strictly a marker of muscle damage, their essential role in muscle remodelling requires satellite cells to be acknowledged in the exercise recovery literature.

Satellite cells are situated beneath the basal lamina, but outside of the sarcolemma and can be measured by obtaining a muscle biopsy for histological assessment. To identify satellite cells, antibodies such as NCAM (CD56) and Pax7 are used to mark the outer border and nucleus of satellite cells (Paulsen, Mikkelsen, Raastad, & Peake., 2012). Transcription factors known as myogenic regulatory factors (MRFs) such as Myf5, MyoD, myogenin and MRF4 have roles in the progression of myogenesis and hence, they can also be used to quantify satellite cell activation (Cornelison & Wold, 1997). Myostatin, a negative regulator of skeletal myogenesis is also important for satellite cell function during muscle growth, and hence, is also widely referred to in the satellite cell literature.

The number of satellite cells present in skeletal muscle rises sharply in the first 24 hours after exercise, and may remain elevated for over eight days (Paulsen, Mikkelsen, Raastad, & Peake., 2012). However, when compared with pre-exercise values, the response of satellite cells to exercise is highly variable even with similar exercise protocols, and does not appear to correlate well with muscle damage (Paulsen, Mikkelsen, Raastad, & Peake., 2012). For that reason, it is often not used as a marker of EIMD but may be measured within the same literature to assess the adaptation response.

1.7.8 The Repeated Bout Effect

Skeletal muscle appears to possess an intrinsic mechanism that reacts to EIMD by offering protection to successive similar muscle damaging exercise if performed within several weeks. This is known as the repeated bout effect. Practically, this means that subsequent bouts of exercise do not induce the same severity of EIMD as the novel bout. Protection tends to occur in an acute manner i.e., untrained individuals performing their second resistance exercise session compared with their first, and the effect is reversible with the magnitude of protection declining over time between bouts from 4-12 weeks (Nosaka et al., 2005). The greatest protection from repeated bouts appears to originate from exercise that has the most potential to cause damage. For example, greater protection is conferred in the elbow flexors compared with the knee extensors, as these generally experience more damage (Hyldahl et al., 2017). Training status may also affect the magnitude of the effect. That is not to say the repeated bout effect cannot be observed in well-trained individuals, but the protection appears to be less (Lavender & Nosaka, 2008).

The mechanisms underlying the repeated bout effect are yet to be definitively understood. However, it has been proposed that alterations to muscle mechanical properties, neural adaptations, structural remodelling of the extracellular matrix, and biochemical signalling all contribute to the phenomenon (McHugh, 2003; Hyldahl et al., 2017). This multi-factorial theory is due to the discrepancies with which the repeated bout effect dampens different markers of muscle damage, suggesting it has an effect through several pathways. For example, the CK response appears to be offered the greatest protection by repeated bouts, whereas the magnitude of protection from DOMS is less. Losses in muscle function have shown to be similar between bouts, but there is some evidence that a repeated bout may expedite recovery (McHugh, 2003). Interestingly, despite repeated bouts blunting DOMS and losses of muscle strength, the inflammatory response to eccentric exercise may become more pronounced, with one study finding marked increases in pro-inflammatory cytokine and macrophage infiltration after an identical resistance exercise bout completed four weeks later (Deyhle et al., 2016).

The repeated bout effect can lend protection from further damage even when the initial bout causes little or no damage (Lavender & Nosaka, 2008). Additionally, the benefits of the repeated bout effect do not appear to be limited to just the exercised muscles; protective effects have been observed in contralateral limbs. In studies assessing the effects of a repeated bout in ipsilateral and contralateral limbs, a protective effect of as much as 40-60 % of that observed in the ipsilateral limb has been reported (Hyldahl et al., 2017). This finding lends strength to the theories that neural and inflammatory adaptations could both contribute to the repeated bout effect alongside the structural adaptations from resistance exercise. This also highlights that whilst EIMD research can be focussed on the specific damaged muscle, adaptation to resistance exercise requires whole-body systems and holistic approaches may be needed to fully comprehend the implications.

1.7.9 Considering the Acute Effects of EIMD in Older Adults

In younger adults, a period of reduced functional capacity following resistance exercise is often of little consequence during day-to-day living. However, in older adults the time frame of reduced physical functioning following an 'overload' to the muscular system may be especially pertinent to understand; not purely for the purpose of prescribing training frequency, which is also important and will be discussed later, but because of the impact that reduced functioning may have on their day-to-day living. Unlike in younger adults, an older individual is likely to have significantly lower baseline physical functioning (Cruz-Jentoft & Sayer, 2019). Therefore, symptoms of EIMD such as muscle soreness, decrements in muscular strength, and fatigue may make it difficult for the individual to continue activities of daily living (e.g. walking up stairs, feeding, ambulating), and in some cases, may also increase falls risk (Moore et al., 2005). Indeed, it has been shown that a single bout of resistance exercise can have an acute negative effect on postural control in older adults (Moore et al., 2005). It was suggested that the change in proprioception causing reduced postural stability was likely due to fatigue induced by the resistance exercise. An association between postural control and falls risk has been confirmed elsewhere (Pajala et al., 2008). This may have implications for the safety recommendations for older adults following exercise, particularly in untrained individuals that are beginning a resistance exercise programme, as they may be more susceptible to damage (Hyldahl et al., 2017). It is therefore important to consider the magnitude and time course of EIMD when prescribing resistance exercise for older adults, and to be aware of strategies that may reduce these deficits.

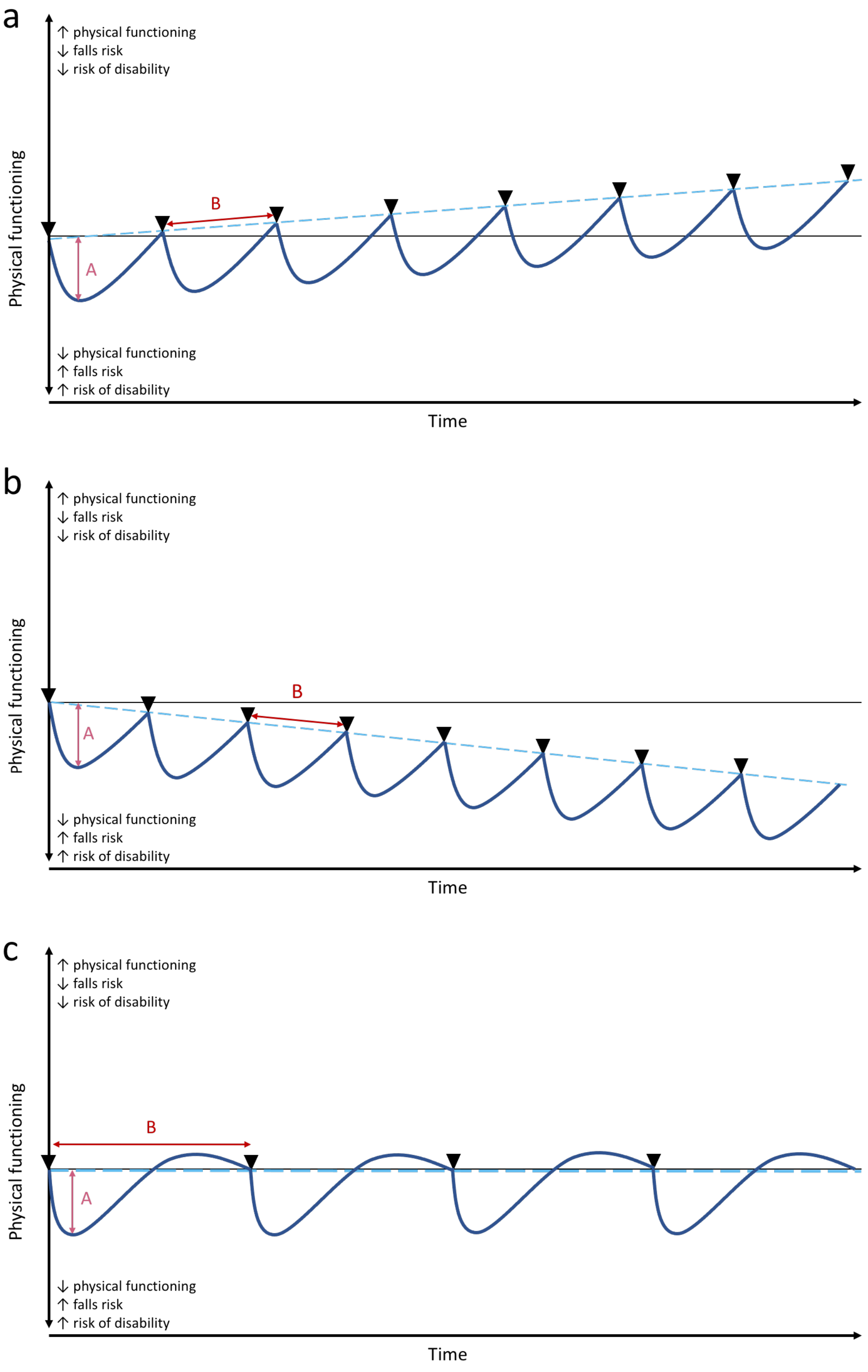

Figure 1.8 Supercompensation Theory applied to older adults. Adaptation to exercise in response to training frequency. A is stable and represents the decrease in functional capacity after training, B represents length of time between training sessions, resistance training sessions are represented by the black triangles: a) training frequency is optimal and matches with supercompensation; b) training is too frequent and results in decreases in functional capacity; c) training is not frequent enough to establish any training effect. (Adapted from Zatsiorsky, Kraemer and Fry, 2020).

1.8 Optimising Exercise Recovery

1.8.1 Why Optimise Exercise Recovery?

It has previously been discussed that resistance exercise can induce adaptation through cycles of damage and repair. To recap, in order to elicit these changes an 'overload' (the performance of challenging resistance exercise) must be applied to the body which may result in inflammation and structural damage to the muscle (Zatsiorsky et al., 2020). In the days following this exercise, the body would recover by re-building itself, so that it is better able to cope with such demands in the future and hence, protect itself from damage. Optimising recovery from resistance exercise may be considered to have two primary aims; (1) expediting recovery, (2) reducing decrements in muscle function and limiting DOMS.

Understanding and manipulating the time needed to recover from resistance exercise has implications for training frequency. Indeed, if sufficient time for recovery is allowed between training sessions, the body can establish a new, greater homeostatic level. In other words, their baseline functional capacity can increase. However, if the time between training sessions is too long, any supercompensation will be lost to detraining and the functional capacity will not improve with chronic training. Equally, if the time between training sessions is too short, the body will not fully recover homeostasis and further training can cause compacted decreases in functional capacity (Figure 1.8). Chronic periods of overload without adequate recovery can have detrimental effects by causing 'non-functional overreaching' or 'overtraining' which may exhibit negative physiological and psychological symptoms (Meeusen et al., 2013). As discussed earlier (See section 1.7.9) this may be particularly unfavourable in older adults whose functional capacity is already reduced.

Identifying the optimal recovery time between resistance exercise sessions is therefore essential to obtain the benefits that have previously been reported. Likewise, if these recovery periods can be reduced by intervention strategies then the individual can perform resistance exercise more frequently, and could make greater improvements in functional capacity within the same time period. It may also be considered important to try to reduce the magnitude of EIMD symptoms an individual experiences within this time period. This is not purely because DOMS is considered unpleasant for the individual, but because reductions in muscle strength can have implications for athletic performance in younger adults, or more critically, for safety and independence in older adults.

A considerable body of literature has characterised the process of exercise recovery in younger adults and athletes. We concur that the same framework of fatigue and supercompensation is applicable to older adults, but the magnitude of reduced functional capacity, and the length of time to recover homeostasis after resistance exercise has not been well documented in this population (Fernandes et al., 2020). Unfortunately, there is some evidence that suggests the processes for adaptation for resistance exercise may be impaired with age. For example, it has been well demonstrated that older adults experience a lower muscle protein synthetic response to both exercise (Doering, Jenkins, et al., 2016) and nutrition (Wall et al., 2015) when compared with younger adults, and it is therefore likely that older adults experience muscle damage differently to their younger counterparts, although the existence and/or magnitude of this effect is yet to be determined (Borges et al., 2016; Fernandes et al., 2020). There is therefore a distinct need for further research in this area to characterise EIMD in older adults and determine if extra precautions should be taken in the exercise recovery period, or if there is a need for altered exercise prescription.

1.8.2 Psychological Components of Exercise Recovery

Clearly, physiological symptoms of EIMD are integral to understanding the time course and magnitude of damage but do not necessarily provide practitioners with sufficient information to prescribe the frequency of resistance exercise that is a realistic target for older adults. In an ageing population, different considerations may need to be made regarding the safety of the individual, and also their willingness to continue participating. To illustrate, in a study by Borges et al. (2018) it was suggested that masters athletes (mean age 55.6 years) may perceive exercise recovery differently to younger athletes after performing high intensity interval training on a cycle ergometer. A moderate effect of age was identified with the older group reporting feeling lower motivation, greater fatigue, and greater muscle soreness in the days following exercise, despite physiological measures of muscle damage displaying no difference between the two groups. This may indicate that although the older group were physiologically recovered from the exercise, they may require more time before being psychologically ready to train again. In spite of the potential implications of this relationship, measures of perceived exercise recovery have not been replicated in other populations, such as untrained older adults, or following resistance exercise protocols. This delay in perceived recovery may negatively affect long-term adherence and hence, this outcome must also be assessed in untrained older adults alongside traditional markers of EIMD.

1.8.3 Current Exercise Recovery Strategies

Limiting the negative side effects of EIMD whilst ensuring maximal adaptation is a main objective of exercise recovery strategies. However, the acceptability and availability of the strategy to the individual may also play a large role in their effectiveness, and should be considered when making recommendations. Current recovery strategies cover a wide variety of methods, including nutrition (Davies et al., 2018; Bowtell & Kelly, 2019), pharmacology (Lundberg & Howatson, 2018), and other alternative strategies (Guo et al., 2017; Ortiz et al., 2019; Cullen et al., 2021).

Alternative strategies for exercise recovery are broad, and include but are not limited to, techniques such as massage, cold water immersion, compression garments, and percussion or vibratory therapy. From recent reviews it is clear that most of these are likely to impart some benefit to the individual in improving recovery. For example, evidence for the benefit of compression garments, vibratory therapy, and cold-water immersion were all classified as 'Level I evidence' in a recent review (Cullen et al., 2021). Level I evidence in this review was defined to be 'evidence from a systematic review or meta-analysis of all relevant RCTs or evidence-based clinical practice guidelines based on systematic reviews of RCTs or three or more RCTs of good quality that have similar results' (Cullen et al., 2021). Other strategies reported in this review (e.g. percussion therapy, hyperbaric therapy or neuromuscular electrical stimulation) showed a possible benefit, but it was concluded that there was no strong evidence for this. With this being said, most alternative recovery strategies are commercialised, and may not be easily accessible or available to all individuals. Equally, some of these strategies carry precautions and may not be suitable or safe for all adults such as cold water immersion, which may be contraindicated by cardiovascular disease, Raynaud's disease, or uncontrolled hypertension (Patel et al., 2019; Glasgow et al., 2014).

Pharmacological interventions such as non-steroidal anti-inflammatory drugs (NSAIDs) have also previously been used as a recovery aid, but their effects remain controversial (Clifford, 2019). This is due to growing concern that their pathway of effect (inhibiting the pro-inflammatory cyclooxygenase (COX) pathways that promote inflammation following muscle injury) may also act to reduce the adaptation to exercise that heavily relies on this inflammatory cascade (Trappe & Liu, 2013). However, some evidence in older adults has reported that consuming NSAIDs daily during a 12-week resistance exercise programme could actually result in greater muscle mass and strength gains 25-50 % above those consuming a placebo (Trappe et al., 2011). However, these results have not been repeated in younger individuals. From the studies that have been conducted in younger adults it is suggested that NSAIDs may attenuate adaptations to resistance exercise, and hence, the recommendation for NSAIDs as a recovery aid may be dependent on the population (Krentz et al., 2008; Lilja et al., 2018). It should also be noted that these inhibitory effects of adaptation are likely to be a result of higher, but not lower doses of NSAIDs (Lundberg & Howatson, 2018). In spite of the potential benefits for recovery, or indeed the drawbacks for adaptation, it should also be questioned whether long-term pharmacological interventions are warranted or safe for exercise recovery. For example, NSAIDs such as paracetamol are associated with liver toxicity, whilst other NSAIDs can affect blood clotting (Andrade et al., 1998). On balance, careful risk-benefit analysis is likely needed before prescribing NSAIDs for exercise recovery in any population, especially in older adults where polypharmacy or drug-drug interactions may cause concern, but they have been shown to be beneficial for reducing DOMS and improving recovery time (Lundberg & Howatson, 2018).

Drawing on a vaguely similar mechanism to NSAIDs, polyphenol supplementation has also been shown to be beneficial for improving recovery from resistance exercise by exerting their effect through anti-inflammatory pathways such as inhibiting the release of reactive oxygen species, and increasing the endogenous anti-oxidant capacity (Peluso et al., 2013). Polyphenols are usually derived from plants, and are found in many dietary sources such as cherries, pomegranates, blueberries, cocoa and soy (Bowtell & Kelly, 2019). However, it can sometimes be difficult to consume optimal doses of polyphenols through diet alone and hence, polyphenols are also provided as a purpose-made supplement over several days or weeks (Duthie et al., 2003). There is growing evidence that polyphenols can reduce a range of markers of EIMD. In a recent review, roughly half of all the studies showed a positive effect on IL-6 concentrations, muscle soreness was attenuated in only one of the studies, but muscle function was improved in both studies that measured it (Bowtell & Kelly, 2019). Similarly to NSAIDs, the effect of polyphenol supplementation on training adaptation remains contentious, with evidence pointing both towards there being no effect, and an attenuation of adaptation (Bowtell & Kelly, 2019).

Another dietary strategy for exercise recovery that has been extensively studied is protein consumption. Protein acts to increase muscle protein synthesis rates in tandem with exercise, and hence, is thought to improve exercise recovery, but is also known to contribute to improved muscular adaptation long-term. Indeed, in young men, consuming a 0.2 grams per kilogram of body mass (g.kg.BM) bolus of isolated egg protein maximally stimulates MPS after exercise (Moore et al., 2009). This can result in a favourable net protein balance and increased satellite cell activity post-exercise, which could accelerate the muscle remodelling process (Phillips & Van Loon, 2011; Farup et al., 2014; Moore et al., 2009), improving both exercise recovery and chronic exercise adaptations. To support this theory of improved recovery, a recent meta-analysis of 13 randomised controlled trials has identified a small to moderate (ES = 0.4-0.7) ergogenic effect of whey protein supplementation for restoring muscle contractile function following resistance exercise from <24 to 96-hours after resistance exercise when compared with a control group (Davies et al., 2018). Whey protein is a high-quality protein source that is rich in essential amino acids, specifically leucine, which is thought to be superior for stimulating MPS (Tang et al., 2009). Whey protein also exerts an effect rapidly after exercise and hence, is widely recommended for exercise recovery (Davies et al., 2018). Other good sources of protein as measured by the protein digestibility corrected amino acid score are animal proteins such as milk, eggs, and meat, but plant-based proteins such as soy and mycoproteins are also considered to be favourable (Phillips & Van Loon, 2011; Monteyne et al., 2020; van Vliet et al., 2015). The timing of protein supplementation can be important, and currently, although the 'optimal window' for protein feeding is yet to be defined, it is recommended that protein be consumed as early as possible after exercise (Phillips & Van Loon, 2011; Pennings et al., 2011).

On the basis of the literature highlighted within this section, it is clear that protein has benefits for expediting exercise recovery, but unequivocally it has been shown that protein consumption can also improve gains in muscle mass and strength in response to resistance exercise (Morton et al., 2018). Additionally, whole food sources of protein are widely available and accessible to most people and is unlikely to have negative side effects, and therefore the remainder of this review will focus on this recovery strategy for use in older adults.

1.8.5 Protein for Exercise Recovery in Older Adults

Despite the possibility that older adults may experience altered recovery kinetics (see section 1.6.3), nutritional aids for exercise recovery in older adults are distinctly understudied. Expectedly, similar mechanisms that alter recovery kinetics in older adults are likely also responsible for the reduced muscle protein synthetic response to protein ingestion and exercise deemed 'anabolic resistance' (Gorissen et al., 2020; Doering, Reaburn, Phillips, & Jenkins, 2016). Anabolic resistance may hamper muscle remodelling and adaptation to exercise, but there is no indication that this cannot be overcome with careful planning of nutrition at least to some extent (Wall et al., 2014; Doering, Reaburn, Phillips, & Jenkins, 2016). Hence the identification of suitable post-exercise nutrition strategies is essential for the ageing population who are now being actively encouraged to participate in resistance exercise to delay sarcopenia and frailty.

As a result of research in young adults, it is now accepted that the consumption of protein after exercise can enhance recovery time, reduce muscle soreness, and improve adaptation to training (Davies, Carson and Jakeman, 2018). However, it has also been shown that supplementing with protein during a resistance exercise programme can increase chronic gains in muscle mass and strength compared with a control group by 38 % and 20 % respectively in older adults (Cermak et al., 2012). However, there is currently very little literature investigating protein supplementation for exercise recovery in older adults. As far as we are aware, only three published studies have applied this knowledge to an exercise recovery intervention in adults > 50 years, and only one has used a resistance exercise protocol (Doering et al., 2017; Clifford et al., 2020; Spoelder et al., 2023). Only one study has been identified that meets the age criteria (>65 years) for older adults that was discussed at the start of this review, but this uses a walking exercise protocol to induce EIMD, rather than resistance exercise. The first of these studies by Doering and colleagues used a sample of eight masters triathletes (52 ± 2 years) to examine the effects of a post-exercise high-protein bolus on acute exercise recovery. It was reported that when a high protein intake (0.6 g.kg.BM) was consumed after 30 minutes of downhill running, loss of peak isometric torque was attenuated (moderate beneficial effect) and perceived fatigue was reduced (large beneficial effect) at 8-hours following exercise compared with a moderate protein intake (0.3 g.kg.BM). This is the only study that provides just one bolus dose of protein after exercise when aiming to investigate the effect on markers of exercise recovery. In the second study, eighteen masters athletes (57 ± 4 years) were supplied with either a higher protein (2.50 g·kg.BM.day) or a moderate protein (1.25 g·kg.BM·day) diet for 48 hours after performing 140 squats with an additional 25% of their body mass. There was no beneficial effect of the higher protein diet on any markers of EIMD (Clifford et al., 2020). The most recent study was published in 2023, and assessed the effect of whey and pea protein supplements compared with a control group on markers of EIMD in older adults (70 ± 6 years) following a 20-30 km walk (Spoelder et al., 2023). Whey protein, but not pea protein or a control, was found to attenuate increases in CK at 24-hours ($p < 0.001$) but had no effect on markers of muscle soreness or muscle strength. This may be due to the relatively small protein dose that the older adults were given (12.5 g every morning and evening for 13 days) as this is likely not enough to maximally stimulate MPS in older adults (Holwerda et al., 2019; Moore et al., 2009). However, this study also did not see any significant effect of time on markers of muscle strength and soreness, suggesting that measurable muscle damage was not induced (Spoelder et al., 2023). This makes it difficult to draw conclusions on the effectiveness of the protein supplement.

At a more mechanistic level, several studies have also begun to investigate how post-exercise dietary protein supplementation affects MPS rates in older adults (Robinson et al., 2013; Yang et al., 2012), and from this literature it has been proposed that higher protein doses up to 0.4 g.kg.BM may be needed to maximally stimulate MPS rates post-exercise in older adults (Moore et al., 2014; Doering, Jenkins, et al., 2016). In a more recent study a dose-response to protein feeding for MPS rates was identified in older adults (Holwerda et al., 2019). It was found that in the first 6 hours after exercise, 15 g (~ 0.19 g.kg.BM) of protein was not sufficient to raise MPS rates above those seen with a placebo, but 30 g (~ 0.37 g.kg.BM) was sufficient, and 45 g (~ 0.55 g.kg.BM) raised MPS rates to above those seen at 30 g. It was acknowledged by Holwerda et al., that ingesting 45 g of protein post-exercise was likely to be somewhat challenging for older adults, and that they may consider fortifying with isolated protein sources to ensure intake is beyond 30 g (Holwerda et al., 2019).

Taken together, it is not entirely clear what the optimal post-exercise protein feeding regime may be, not just to maximally stimulate MPS, but also to create meaningful differences in measures of EIMD in older adults. This is partly due to a lack of studies investigating both MPS response and EIMD together in older adults but could also be attributed to the need for more studies investigating responses to various proteins and exercise types.

1.9 Milk as a Recovery Supplement

The beneficial effects of post-exercise protein supplementation on exercise recovery has been well documented in younger adults (Pasiakos et al., 2014; Davies et al., 2018). In a recent meta-analysis, post-exercise intake of whey protein, which is rich in the amino acid leucine, was shown to expedite the recovery of muscle function in young adults (Davies et al., 2018). A whole food nutritional intervention that has gained popularity recently is cow's milk, which has both a high whey and leucine content, alongside a favorable macro and micro-nutrient content that could contribute to exercise recovery.

1.9.1 Nutritional composition

Liquid cow's milk is widely accessible and available, coming in a range of fat contents commonly sold as skimmed milk, semi-skimmed milk and whole milk. This variation in fat content leads to differing energy contents per unit, but otherwise, nutritional composition is similar between the beverages.

Per 100 mL, skimmed milk contains <0.5 g of fat and 37 kcal, with semi-skimmed and whole milk containing 1.8 g and 3.7 g of fat, and 50 kcal and 66 kcal respectively. Protein (3.5-3.6 g/100 mL) and carbohydrate (4.7–5.0 g/100 mL) content is similar regardless of fat content (James, Stevenson, Rumbold, et al., 2019). The fat content in milk is comprised of a mixture of saturated fatty acids and mono-unsaturated fatty acids, alongside a low amount of essential fatty acids such as poly-unsaturated fatty acids (PUFAs). This includes linoleic acid, α-linoleic acid, and long-chain *n*-3 fatty acid that all have functions in cell membrane and are deemed to be metabolically active (Haug et al., 2007; Granic, Hurst, Dismore, Aspray, Stevenson, Miles D Witham, et al., 2020).

On average, milk contains approximately 3.6 g of high-quality protein per 100 mL, of which approximately 80 % is whey protein, and the remaining 20 % casein. This whey protein is estimated to be approximately 13.4 % leucine, which is thought to be the most potent amino acid for stimulating MPS (Granic, Hurst, Dismore, Aspray, Stevenson, Miles D Witham, et al., 2020). The benefits of whey for exercise recovery have been discussed previously, but casein also provides a distinct benefit for MPS. Indeed, casein can stimulate net muscle protein synthesis to similar levels to whey, but the digestive properties of casein likely slow the rate of amino acid appearance in the blood, and thus, casein exerts effects on MPS for longer periods (Tipton et al., 2004). These casein proteins are also bioactive peptides, which can have several physiological benefits including being antihypertensive, antithrombotic, anti-microbial and immunomodulatory (Mills et al., 2011).

Milk also contains several essential micronutrients. On average, 500 mL of whole milk would contain 15–20% of the dietary recommended intake for vitamin A, 40–50% for calcium, 90% for vitamin B12, 60–80% for riboflavin, 30% for selenium, and 50 % of the requirements for iodine, alongside other minerals such as phosphorus, zinc, and magnesium (Granic et al., 2020) . Importantly for an older population, alongside the aforementioned bioactive peptides and PUFAs, selenium and zinc, can have anti-oxidative properties. Hence, milk can be considered beneficial for human health, regardless of its ability to improve exercise recovery.

1.9.2 Reasons for the Preference of Milk over Other Whole Foods

It has been shown that the ingestion of milk proteins following muscle damaging exercise can stimulate MPS to similar levels as whey protein (Mitchell et al., 2015). As a readily available and cheap food source needing no or minimum preparation, cow's milk may therefore potentially be a useful recovery strategy for older adults. It should be remembered that exercise recovery is not wholly determined by rates of MPS, and that other factors will also contribute to acute recovery. For example, James et al (2019) suggested that the five main nutritional considerations for exercise recovery were; (1) optimisation of muscle protein turnover; (2) glycogen resynthesis to replace used carbohydrate stores in muscle and liver; (3) rehydration to replace water stores lost though sweating; (4) management of any exercise-associated muscle soreness; and (5) appropriate management of energy balance (James, Stevenson, Rumbold, et al., 2019). The importance of each of these will be dependent on the exercise being performed. However, it is clear that the unique composition of milk can contribute to each of these considerations and hence, could be considered an optimal post-exercise recovery beverage.

For a supplement to be used regularly by a large proportion of the population it stands to reason that it must be affordable and widely available. Despite the recent cost of living crisis, milk still remains an affordable commodity for most. Indeed, one litre of milk could cost as little as 69 p from a major UK supermarket (Data obtained from www.sainsburys.co.uk and is based on a price of £2.35 for six pints of semi-skimmed milk). Milk is also already an established part of the diet for many older adults (Singh et al., 2015), and hence, the addition of milk as a recovery supplement should be acceptable to this population. For older adults, it is also particularly important that any additional food stuffs do not negatively impact their appetite as this group are already at a high-risk for low energy-intake (Morley & Silver, 1988), with the complication of this being reductions in muscle mass. Fortunately, when compared with other high-protein dairy foods, milk has been shown to have a much smaller effect on appetite and satiety (Law et al., 2017). Similarly, when compared with a carbohydrate beverage, milk does not significantly reduce energy intake or appetite (Brown et al., 2016). Milk is therefore likely to be a recovery strategy that has less impact on subsequent energy intake compared with other whole foods, which could be particularly important in older adults.

Another reason that milk may be an ideal post-exercise recovery strategy is the potential to maximise gains in muscle mass. Two studies have demonstrated that if ingested chronically after resistance exercise, 500 mL of milk has the potential to increase gains in lean body mass compared with carbohydrate or soy drinks over a 12-week resistance exercise programme (Hartman et al., 2007; Josse et al., 2010). Another study also found a tendency for milk consumption to result in greater accrued lean mass over a 10-week resistance exercise programme compared with a carbohydrate drinks, but results from this study were not significant (milk; +1.6 kg.FFM, carbohydrate; +0.8 kg.FFM, $p = 0.13$).

1.9.3 The Protein Synthetic Response to Whole versus Skimmed Milk

Interestingly, it has been suggested that fat and carbohydrate content may alter the protein synthetic response to certain foods. Indeed, despite fat and carbohydrates inability to stimulate positive net protein balance when ingested individually, when ingested simultaneously with protein the muscle protein synthetic response appears to be greater than protein alone (Miller et al., 2003; Elliot et al., 2006).

Following a series of studies that determined the ingestion of fat and sucrose alongside milk proteins increased whole body nitrogen retention (a marker of net protein balance), Elliot and colleagues aimed to replicate these findings using a naturally occurring food containing all three macronutrients – milk. To determine the effects of the fat content of milk on muscle protein balance after resistance exercise, 24 young untrained volunteers were randomly assigned to one of three experimental groups; (1) 237 g fat-free milk (2) 237 g whole milk, or (3) 393 g of fat-free milk isocaloric to 237 g of whole milk. Using threonine and phenylalanine uptake as markers of MPS, it was concluded that although all three groups significantly stimulated MPS above resistance exercise alone, threonine uptake was significantly greater in the four hours after consuming 237 g whole milk compared with both 237 g fat free milk and the isocaloric fat free milk (393 g) (Elliot et al., 2006). These findings suggest that whole milk could have the potential to stimulate MPS to a greater extent than skimmed milk following resistance exercise, but unfortunately no further evidence of this effect in milk could be found.

1.9.4 Milk for Exercise Recovery in Younger Adults

Milk has continually been shown to be an effective exercise recovery strategy in younger adults (Rankin et al., 2018, 2015; Cockburn et al., 2008, 2012; Molaeikhaletabadi et al., 2022).

The potential of milk for minimising symptoms of EIMD was first reported in 2008 by Cockburn et al. who found that two servings of 500 mL of milk, or a flavoured milk drink were effective in maintaining concentric knee flexion performance and attenuating increases in CK and Mb after performing six sets of ten repetitions of unilateral eccentric-concentric contractions of the knee flexors compared with a commercially available carbohydrate-based sports drink (Cockburn et al., 2008). This work was followed by the same research group to determine if there was a dose-response benefit of milk consumption on markers of EIMD. Using three matched groups of eight males each, it was concluded that 500 mL of milk was enough to limit decrements in isokinetic peak torque of the knee flexors, and increases in CK and Mb, compared with water at 24- and 48-hours post-exercise. However, there was no additional benefit of increasing milk intake to 1000 mL (Cockburn et al., 2012). The findings of the first two studies were repeated in 2015 to include data in both males and females. 16 males and 16 females were assigned to one of four groups, with eight males and females each consuming either 500 mL of milk or a carbohydrate drink. Using the same muscle damaging protocol as previously reported (Cockburn et al., 2008, 2012), the results of this study confirmed that peak torque decrements following muscle damaging exercise could also be attenuated at 24-, 48-, and 72-hours after exercise in females consuming a milk supplement immediately after exercise (Rankin et al., 2015). For the first time in this study it was also shown that milk had potential to attenuate increases in DOMS at all time-points post-exercise when compared with a carbohydrate drink, compared with Cockburn et al., (2012) who only found a positive effect at 48-hours. Also observed in this study were slight discrepancies in the efficacy of milk consumption for moderating EIMD in males versus females. Indeed, the effect of milk in males was mostly unclear, but the authors suggested these differences may be due to the greater relative protein intake in females (0.27 g.kg.BM) compared with males (0.22 g.kg.BM) as a result of body mass differences between groups.

Milk has also been shown to be beneficial for recovery following a sprinting and jumping protocol. Although not directly relevant for this review, it is noteworthy that 500 mL of milk was protective of peak torque and countermovement jump height in female team-sport athletes, but had an unclear effect on muscle soreness and CK (Rankin et al., 2018). However, a low fat chocolate milk has since been used effectively to reduce muscle soreness in females following 90-minutes of badminton playing (Molaeikhaletabadi et al., 2022), and hence, it is possible that milk still provides a beneficial effect for muscle soreness following intensive exercise.

As a whole, these studies provide a promising evidence base for the efficacy of milk in aiding exercise recovery. These benefits are likely to be attained through the consumption of 500 mL of milk, although in populations that may be more anabolically resistant, it stands to reason that additional volume may be needed to maximally stimulate MPS. Additional research may be needed that exercises different muscle groups and uses other exercise protocols, as conclusive data are currently limited only to concentric contractions of the knee flexors.

1.9.5 The Acceptability of Milk and Exercise Interventions in Older Adults

Despite evidence for the role of milk in enhancing exercise recovery, current evidence of its acceptability is scarce. We have identified one recent study which explored older adults' attitudes and barriers to engaging in a resistance training program and consuming a recovery drink (bovine milk) after exercise (Dismore et al., 2020). When performing resistance exercise twice per week for six weeks, 29 community dwelling older adults (> 65 years) were asked to consume 500 mL of milk immediately after exercise, and 500 mL of milk throughout the rest of the day (Granic et al., 2019). Compliance to milk consumption in this study was 97.13 % in those drinking whole milk, and 98.33 % in those assigned to skimmed milk. The data collected suggested that older adults considered milk to be an acceptable post-exercise recovery drink. Self-perceived health improvement, knowledge acquisition, social wellbeing, professional support, and a fun environment were all identified as motivators for engagement in the program. Affordability, environmental factors, and concerns over negative health outcomes were cited as barriers for continued participation. Amongst those individuals, only two participants found the volume of milk they were asked to consume was 'somewhat' a barrier, and for some consuming milk after exercise was seen as a 'reward' and 'refreshing' (Dismore et al., 2020). These findings will aid greatly in understanding why older adults may or may not choose to participate in a resistance exercise program and allows us to tailor future interventions to encourage continued engagement.

1.10 Summary of Literature Review

Resistance exercise is a widely advocated treatment for improving muscle health and preventing sarcopenia in older adults. Despite a considerable body of literature demonstrating the benefits of resistance exercise in older adults and the inevitability of exercise induced muscle damage, the process of recovery from resistance exercise is fundamentally understudied in this population. It is possible that the mechanisms contributing to declines in muscle mass and function as we age could also exert an effect on the recovery process following resistance exercise, or present safety concerns for older adults, although the evidence for this remains inconclusive. Irrespective of the potential alterations in the exercise recovery process, there remains a strong case for protein, or more specifically protein-rich whole foods, to expedite this process and ensure maximal adaptation to training in older adults. However, this is currently unreported in the literature, and hence, the efficacy of such interventions alongside their acceptability in the target population presents a large gap in our knowledge.

1.11 Summary of Experimental Hypothesis and Aims

The purpose of this thesis is to draw together the literature describing exercise-induced muscle damage and exercise recovery in older adults, and begin to move forward in identifying suitable whole food interventions to aid recovery, whilst concurrently investigating older adults' knowledge and attitudes towards resistance exercise, exercise recovery, and exercise recovery strategies.

Chapter 2: This scoping review aimed to chart the current evidence surrounding exercise-induced muscle damage, and recovery from resistance exercise in older adults. This review collates and summarises data from all studies reporting various indirect markers of exercise-induced muscle damage in older adults in an attempt to form a coherent view of the literature and provide insights for future research in the area.

Chapter 3: This study aimed to understand the perspectives of community-dwelling older adults, and determine their current knowledge of resistance exercise, exercise recovery, and their attitudes towards exercise recovery strategies. Specifically, this survey collected information on their physical functioning, their physical activity status, their barriers and motivators for participating in resistance exercise, their knowledge and experiences of exercise recovery, and their attitudes towards exercise recovery interventions such as cow's milk. This survey provides insights into how older adults perceive the exercise recovery process, and how they may engage in exercise recovery processes after recommended exercise training.

Chapter 4: The aims of this study were two-fold. Firstly, given the current evidence for the benefits of milk for exercise recovery in younger adults, and the potential for fats to aid recovery, we examined the effectiveness of whole bovine milk for expediting exercise recovery, or attenuating muscle damage in older adults following resistance exercise, versus skimmed milk and a carbohydrate control drink. Secondly, this study aimed to assess the applicability of any findings to a real-world setting by gathering further data regarding older adult's views on exercise recovery, exercise recovery supplements, and using milk as an exercise recovery supplement via an exit survey of study participants.

Chapter 2 : Recovery from Resistance Exercise in Older Adults - a Systematic Scoping Review

2.1 Abstract

Aim

This chapter aimed to comprehensively chart the current literature surrounding exercise-induced muscle damage and recovery from resistance exercise in older adults. This review collates and summarises data from all studies reporting various indirect markers of exercise-induced muscle damage in older adults in an attempt to form a coherent view of the literature and provide insights for future research in the area.

Methods

This chapter reports the findings of a systematic scoping review. The following electronic databases were searched using a combination of MeSH terms and free text: MEDLINE, Scopus, Embase, SPORTDiscus and Web of Science. Studies were included if they reported any markers of exercise induced muscle damage after performing a bout of resistance exercise in older adults aged 65 years and over. Data was extracted from eligible studies using a standardised form. Studies were collated and are reported by emergent theme or outcomes.

Results

A total of 8790 possible articles were identified and 33 original research articles were included. Findings are reported by theme; age differences in recovery from resistance exercise, symptoms of exercise induced muscle damage, and biological markers of muscle damage.

Conclusions

There is limited research assessing recovery from resistance exercise in older adults with literature in this area inconsistent in both study protocol and findings. Across all measures of exercise induced muscle damage, data in females is lacking when compared with males, and rectifying this discrepancy should be a focus of future studies.

2.2 Introduction

Resistance exercise, also known as strength training and/or resistance training, has been shown to be effective in improving muscle health in older adults (Peterson et al., 2010). However, despite considerable research describing the potential benefits of resistance exercise in older adults, exercise recovery, and the process of muscle repair and adaptation following intense exercise, is distinctly understudied. Indeed, little is known regarding how older adults recover from individual exercise sessions that may be performed as part of a resistance training programme.

Traditionally, resistance exercise has been performed by athletes to improve physical performance, and as such, a large proportion of the literature surrounding exercise recovery and muscle damage is concentrated on younger adults. According to the theory of adaptation (Selye, 1951; Bompa & Buzzichelli, 2018), the recovery period is considered highly important when prescribing exercise programs that aim to produce distinct physiological changes through repeating cycles of muscle damage and repair. Generally, literature in younger adults seeks to understand the muscle damage and recovery cycle as a means to optimise training adaptations for sporting performance, but this may not be as relevant for an older population. Indeed, some literature suggests that ageing results in greater muscle damage, and that the time course of the exercise recovery process could be prolonged with age (Fernandes et al., 2020). These potential differences cast doubt on the applicability of pre-existing research with younger participants. Additionally, advancing age presents a range of alternative considerations when designing exercise programs (Zaleski et al., 2016), as both the psychological (Fell et al., 2008; Borges et al., 2018) and physiological (Close et al., 2005) way in which exercise induced muscle damage is experienced may present challenges to older adults that are not deemed as relevant in younger individuals.

A main aim of resistance exercise for older adults is the maintenance of muscle mass and strength, yet any transient decrements in physical functioning resulting from intense exercise in these individuals could hinder their ability to perform habitual activities such as climbing a flight of stairs, or acutely increase their risk of falls (Moore et al., 2005; Helbostad et al., 2010; Papa et al., 2015). Therefore, whilst optimising exercise prescription for training adaptations remains essential, we must also consider the effects that resistance exercise has on individuals with lower physical functioning, and their ability to cope with symptoms of muscle damage in the days following exercise. A greater understanding of this topic is needed in order to establish how these symptoms may interact with the daily lives of older individuals, the optimal frequency of resistance training considering the time course of exercise recovery, and how they affect continued engagement with resistance exercise. Indeed, an ability to optimise training adaptations to maintain muscle strength with advancing age, whilst mediating any adverse effects of exercise induced muscle damage should be an important aim of all exercise prescription for older adults.

This chapter aimed to map the current evidence surrounding exercise-induced muscle damage, and recovery from resistance exercise in older adults. Specifically, this review aimed to establish; (a) which population groups have been studied; (b) how the exercise recovery process has been characterised; (c) what acute post-exercise effects of resistance training have been documented in older adults; (d) the time-course of exercise recovery in older adults and; (e) what variables (if any) have been shown to alter the exercise recovery process in this population.

2.3 Methods

The protocol for this systematic scoping review has been published previously (Hayes et al., 2022). This review was reported in accordance with the guidance from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) (Tricco et al., 2018). The review reports on the current state of the literature regarding the acute effects of resistance exercise in older adults and follows the framework for scoping reviews first outlined by Arksey and O'Malley (Arksey & O'Malley, 2005) and further refined by the Joanna Briggs Institute (Peters et al., 2015). This framework requires the following steps: (a) *identifying the research question*; (b) *identifying relevant studies; (c) study selection; (d) charting of the data;* and (c) *collating, summarising and reporting the results.*

2.3.1 Identifying the Research Question

The overall aim of this review was to assess the current evidence surrounding exercise-induced muscle damage, and recovery from resistance exercise, in older adults. The research questions were defined as follows:

1. Which population groups have been included in current research (e.g., age, sex, training status) and what are the key characteristics of the resistance exercise undertaken (e.g., intensity, volume, contraction type)?

2. How has recovery been characterised? What are the key outcomes (both subjective and objective) that have been measured to quantify exercise induced muscle damage and the exercise recovery process?

3. What are the acute post-exercise effects of resistance exercise, including physiological markers of exercise-induced muscle damage and ability to complete daily tasks, and what is the time-course for these effects?

4. Which variables have been shown to affect the extent of muscle damage and the time course of the exercise recovery process in an older population (e.g., individual characteristics, nutrition, other recovery strategies)?

We define the key terms of the research questions as follows:

- *Resistance exercise*: any physical activity which produces skeletal muscle contraction/s by using an external resistance or weight.
- *Exercise induced muscle damage:* A temporary disturbance in the function and/or structure of skeletal muscles as a result of intense or unaccustomed exercise
- *Exercise Recovery:* The process of resolving physiological and psychological disturbances that may occur as a result of performing intense or unaccustomed exercise. This process begins once exercise has ceased.

For the purpose of this review, we defined the period during which exercise recovery occurs to be immediately after, and up to ten days following, the exercise session. We acknowledge that some symptoms of muscle damage may extend past this time-frame after very intense exercise, but this is unlikely to be representative of exercise performed by an older population. This time-frame also allowed us to ensure we were identifying studies that measure exercise recovery, as opposed to chronic training adaptations.

2.3.2 Identifying Relevant Studies

The following electronic databases were searched on the 6th April 2021 using a combination of MeSH terms and free text: MEDLINE, Scopus, Embase, SPORTDiscus and Web of Science. In addition, reference lists of all identified articles were screened for additional studies.

The search strategy included terms related to the population of interest (i.e., adults, older adults, elderly) in combination with the exercise mode (i.e., resistance training, weight training, weight-lifting, resistance exercise) and the outcomes of interest (i.e., muscle damage, exercise recovery, muscle soreness, muscle function, muscle strength, isometric strength, creatine kinase, inflammation, perceived recovery). The full search strategy is available in the appendices (Appendix A). Due to the nature of scoping reviews, the search was designed to be as broad as possible, to minimise the risk of missing relevant material. Studies were included if they met the eligibility criteria set out in Table 2.1.

All primary research articles that met the criteria were included in the review. Studies that contained older adults of both sexes from all races/ethnicities, settings, and geographical areas were included. We did not exclude studies that contain a younger age group in addition to older adults. Although we did not require studies to exclusively include healthy, disease free older adults, studies that were conducted within specific clinical populations were excluded. We also excluded trials where there was no 'exercise only' condition (i.e., where all conditions have received a recovery intervention) and where there was therefore no data on the participants' usual response to resistance exercise.

Different outcomes than those stated in Table 2.1 may have been used to measure exercise induced muscle damage or exercise recovery. Any other parameter not mentioned in Table 2.1 that was agreed by two reviewers to be assessing exercise induced muscle damage or exercise recovery was included. We considered any method used to measure these outcomes in the included studies (e.g., for physical functioning we accepted both the chair stand test and the timed up and go test).

Table 2.1 Study selection criteria

	Inclusion	Exclusion
Population	Older adults aged 65 years or over.	Articles utilising specific clinical populations (e.g. cancer patients)
Intervention	Performance of a resistance exercise session	No restrictions on the intensity of the resistance training, or the muscle groups used during this exercise.
Comparison	No comparator group necessary	Nil exclusion criteria.
Outcome	All direct and indirect measures of acute muscle damage and exercise recovery including but not limited to; muscle strength, physical functioning, muscle soreness, muscle power, perceived recovery, creatine kinase, inflammation, myoglobin, range of motion, and limb circumference. Ultrastructural muscle damage will also be considered as an outcome of interest.	Nil exclusion criteria.
Publication Type	Published primary research studies, including both qualitative and quantitative research. Abstracts of unpublished studies for which authors can be contacted and provide sufficient information to enable accurate analysis.	Literature reviews. Systematic reviews. Meta-analyses. Trial protocols. Book chapters. Text. Conference abstracts Opinion papers. Letters. Not published in English.

2.3.3 Study Selection

All eligible articles were uploaded to Zotero 5.0 where duplicate articles were removed. The initial screening of the articles was conducted by the authors. To ensure the suitability of the selected studies for the research objectives, two reviewers (EJH and CH) screened by title and abstract. If the eligibility of a study was not clear from the abstract, a full-text article was obtained. Full text screening of the subsequently selected articles was conducted by two reviewers independently (EJH and CH). Every effort was made to obtain full-text articles of the selected articles including web searching, contacting the necessary authors, and consultation of a university librarian. Discrepancies between reviewers was initially sought to be rectified by discussion. In the case of no resolution, a third reviewer (AG) was asked to determine a consensus.

2.3.4 Charting of the data

Data was extracted from all eligible studies using a standardised form to chart the data developed by three reviewers (EJH, CH, and AG). As is the nature of a scoping review, this form was continually reviewed by the reviewers throughout the data extraction process to ensure all relevant information was gathered to successfully address the aim of the scoping review. The purpose of this form was to gather all of the relevant information surrounding the exercise recovery process in older adults. Data was charted by one author (EJH) and checked by a second author (CH). Any disagreements were resolved first by discussion between the two reviewers, or further adjudicated by the third (AG) if a unanimous decision could not be made.

Information of interest included the following:

- Study characteristics: year of publication, journal, aims and objectives of the study, study design, sample size, study setting
- Participant characteristics: population sampled, age (e.g., mean with standard deviation and range), sex (e.g., percentage of male/female participants), training status (e.g., untrained or resistance trained).
- Resistance exercise intervention protocol (e.g., exercises performed, muscle groups used, training intensity, training volume, contraction type, and any other relevant information).

- Outcome results (e.g., finding relevant to exercise recovery or exercise induced muscle damage)
- Time frame of outcome measures (e.g., at what time-points were data collected in relation to the resistance exercise protocol)
- Presence of any comparison groups (e.g., young adults, or a nutritional intervention)
- Key relevant findings and conclusions

2.3.5 Collation, summarization, and reporting of the results

A PRISMA flow diagram is used to report the final numbers of relevant articles included in the review. Both quantitative and qualitative data from relevant studies is presented in a tabular format, with further narrative description if necessary. The study findings are synthesised in a narrative format based on the research questions and any themes that were identified during data extraction. The implications of these findings and identified gaps in the literature are also discussed in narrative form.

Our key findings, alongside other relevant exercise science literature are discussed in relation to the prescription of resistance exercise in older adults. The review also highlights the key areas where additional and/or better-quality evidence is needed before specific recommendations can be made regarding exercise recovery in older adults.

2.4 Results

The results of this review are organised by themes that were recurrent throughout the literature, or that the authors deemed relevant for advancing current knowledge. Age differences in recovery from resistance exercise are presented first, followed by symptoms of exercise induced muscle damage, biological markers of muscle damage, and finally, factors that may affect exercise induced muscle damage and exercise recovery in older adults. For the purpose of this review, circulating muscle proteins include creatine kinase (CK), myoglobin, and lactate dehydrogenase (LDH) as these are the most commonly reported within the literature.

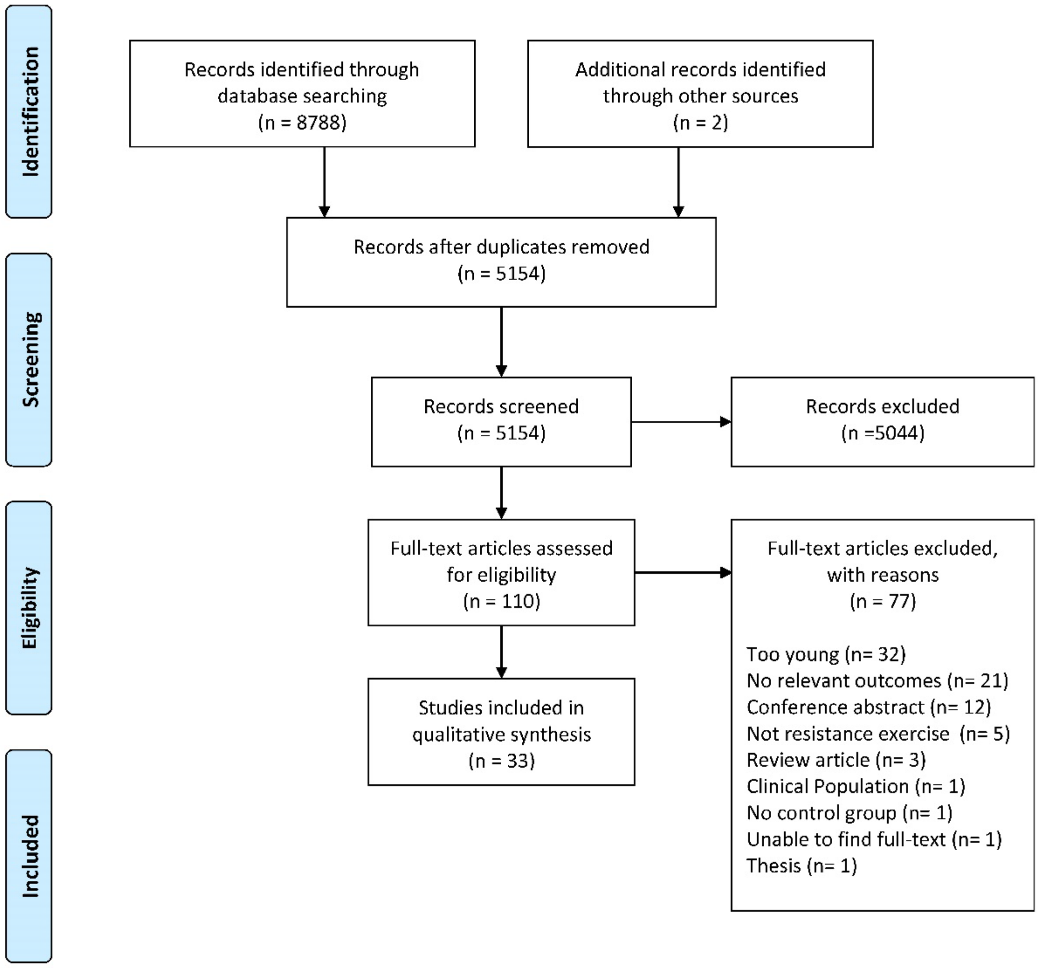

Figure 2.1 PRISMA flow diagram.

2.4.1 Study Selection

Following the initial database search, 8790 records were identified (Figure 2.1). Once duplicates were removed, 5154 titles and abstracts remained, and were screened for inclusion, resulting in 110 full-text articles being screened. Of these, 77 were excluded and 33 were included for qualitative synthesis.

2.4.2 Age Differences in Recovery from Resistance Exercise

The Effect of Age on Exercise-Induced Muscle Damage in Males

Seven studies were found that reported the effects of age on exercise-induced muscle damage in older males exclusively (Table 2.2). Four of the studies reported on symptoms of muscle damage such as physical functioning and muscle soreness (Andrew P. Lavender & Nosaka, 2006; A. P. Lavender & Nosaka, 2006; Lavender & Nosaka, 2007), one reported on the inflammatory response (Przybyla et al., 2006), and two reported the satellite cell response (Snijders et al., 2014; Dreyer et al., 2006). Three studies originated from the same research group, and used the same eccentric exercise protocol of the elbow flexors (6 x 5 repetitions at 40 % maximal isometric strength)(Andrew P. Lavender & Nosaka, 2006; A. P. Lavender & Nosaka, 2006; Lavender & Nosaka, 2007). One study used an eccentric protocol of the knee flexors (Dreyer et al., 2006), and the remaining three employed a concentric exercise protocol for the lower limbs (Przybyla et al., 2006; Nikolaidis, 2017; Snijders et al., 2014).

Six out of the seven studies reported at least one variable that had a significantly smaller magnitude of change in older adults compared with the young group, and as such reported less EIMD in the older group (Andrew P. Lavender & Nosaka, 2006; A. P. Lavender & Nosaka, 2006; Lavender & Nosaka, 2007; Nikolaidis, 2017; Dreyer et al., 2006; Snijders et al., 2014). Przybyla et al (2006) did not record any significant differences between groups, but the older group (71 ± 5) did tend to have a smaller increase in macrophage number and cytokine response post-exercise compared with the younger group (32 ± 7)(Przybyla et al., 2006). None of the studies observed full recovery of symptoms of exercise-induced muscle damage, despite some studies continuing for ten days post exercise.

The Effect of Age on Exercise-Induced Muscle Damage in Females

Three articles aimed to understand the effect of age on exercise induced muscle damage in females exclusively (Table 2.3). Two of these studies reported one study in two separate papers, and hence, only two unique studies are reported (Clarkson & Dedrick, 1988; Dedrick & Clarkson, 1990).

Clarkson and Dedrick (1988), and Dedrick and Clarkson (1990) both used an eccentric resistance exercise protocol consisting of 24 repetitions of the elbow flexors at 115 % maximal isometric strength in twenty healthy females. Ploutz-Snyder et al. (2001) also used eccentric contractions, but their exercise protocol was ten sets of ten repetitions of the knee extensors at 75% eccentric 1-RM.

The older females (67 ± 5) within the Clarkson and Dedrick (1988), and Dedrick and Clarkson (1990) study experienced greater decreases in maximal isometric strength and relaxed elbow angle, and also recovered these measures slower than the younger group (24 ± 3) in the days following exercise (Clarkson & Dedrick, 1988; Dedrick & Clarkson, 1990). No differences in muscle soreness, flexed elbow angle, CK, reaction time, or movement time were observed between the two groups. Similar results were observed by Ploutz-Snyder et al., with concentric and eccentric 1-RM both decreasing more in older adults, and taking longer to recover after eccentric exercise of the knee extensors.

Table 2.2 Studies Reporting the Effect of Age on Exercise-Induced Muscle Damage in Males

Study	Subjects	Age (years)	Exercise	Main Outcomes	Effect of Age on Magnitude of Change	Effect of Age on Time to Recovery	Other findings
Dreyer et al. (2006)	19 healthy males (10 young, 9 older)	60-75 (mean age not given)	12 reps, followed by 5 x 16 reps of single-leg maximal eccentric isokinetic loading of the knee extensors	Satellite cell content	↓*	N/A	
Lavender & Nosaka (2006a)	20 healthy males (10 young, 10 older)	19 ± 0, 71 ± 2	6 x 5 reps eccentric contractions of elbow flexors @40% maximal isometric strength	MIVC Muscle soreness CK Mb Range of motion Limb circumference	↓* ↓* ↓* ↓* ↓* ↔	Not recovered ↓ Not given Not given ↓ Not recovered	
Lavender & Nosaka (2006b)	18 healthy males (10 young, 8 older)	20 ± 2, 71 ± 4	6 x 5 reps eccentric contractions of elbow flexors @40% maximal isometric strength	MIVC Muscle soreness CK Mb Range of motion Limb circumference	↓* ↓* ↓* ↓* ↓* ↔	Not recovered ↓ Not recovered Not recovered Not recovered Not recovered	Repeated bout (4-wks) did not confer a protective effect for MIVC but it did for soreness and Mb
Przybyla et al. (2006)	34 healthy males (17 young, 17 older)	32 ± 7, 71 ± 5	3 x 8 reps for bilateral leg press, leg curl, and leg extension @80% 1-RM. Plus 4th set to failure.	Macrophage number Cytokine expression	↓ ↓	N/A N/A	At rest, older adults had higher levels of IL-1β, IL-1RA, and IL-10
Lavender and Nosaka (2007)	32 healthy males (10 young, 12 middle-aged, 10 older)	20 ± 2, 48 ± 7, 71 ± 4	6 x 5 reps eccentric contractions of elbow flexors @40% maximal isometric strength	MIVC	↓*	Not recovered	No changes in force fluctuations at any intensity (30%, 50%, 80% MIVC)
Snijders et al. (2014)	20 healthy males (10 young, 10 older)	22 ± 1, 73 ± 1	6 x 10 reps of horizontal leg press and leg extension @75% 1-RM	Satellite cell content MyoD+ expression	↓* ↓*	Not recovered Not recovered	

Nikolaidis et al. (2017)	20 healthy males (10 young, 10 older)	22 ± 4, 67 ± 5	5 x 15 reps of back squat @75 % 1-RM on a smith machine	MIVC	↓*	N/A
				Muscle soreness	↔	N/A
				CK	↔	N/A
				Range of motion	↔	N/A
				Joint position sense	↔	N/A

data extracted from figures, * significantly different from baseline, reps repetitions, 1-RM one-repetition maximum, MIVC maximal isometric voluntary contraction, CK creatine kinase, Mb myoglobin, h hours, wks weeks, ↓ less change compared to young, ↔ no difference between groups.

Table 2.3 Studies Reporting the Effect of Age on Exercise-Induced Muscle Damage in Females

Study	Subjects	Age (years)	Exercise	Main Outcomes	Effect of Age on Magnitude of Change	Effect of Age on Time to Recovery	Other findings
Clarkson & Dedrick (1988)	20 healthy females (10 young, 10 older)	24 ± 3, 67 ± 5	24 reps eccentric contractions of elbow flexors @115% maximal isometric strength	Relaxed elbow angle Flexed elbow angle Muscle soreness CK	↑* ↔ ↔ ↔	↑ ↔ ↔ Not recovered	
Dedrick & Clarkson (1990)	20 healthy females (10 young, 10 older)	24 ± 3, 67 ± 5	24 reps eccentric contractions of elbow flexors @115% maximal isometric strength	MIVC Muscle soreness Reaction time Movement time	↑ ↔ ↔ ↔	↑ ↔ ↔ ↔	No significant difference in magnitude of strength loss, but older recovered slower
Ploutz-Snyder et al. (2001)	12 healthy females (6 young, 6 older)	23 ± 4, 66 ± 5	10 x 10 reps unilateral eccentric contractions of knee extensors @75% eccentric 1-RM	Concentric 1-RM Eccentric 1-RM	↑* ↑*	↑ ↑	12-wk RT programme attenuated declines in muscular strength, losing only 14% (Con) and 12% (Ecc) of 1-RM strength

data extracted from figures, * significantly different from baseline, reps repetitions, 1-RM one-repetition maximum, MIVC maximal isometric voluntary contraction, CK creatine kinase, Con concentric, Ecc Eccentric, h hours, wks weeks, ↑ greater change compared to young, ↔ no difference between groups.

2.4.3 Symptoms of Exercise-Induced Muscle Damage

Physical Function

Fourteen studies measured an outcome relating to physical function in adults over 65 years of age (Table 2.4). The most common measure of physical functioning was maximal voluntary contraction (MVC) (12/14 studies). One study used one repetition maximum (1-RM) to assess strength (Ploutz-Snyder et al., 2001), and one study used neither MVC or 1-RM (Marques et al., 2019), instead measuring counter-movement jump height, hand grip strength, and seated medicine ball throw performance. The Timed-Up-and-Go test (TUG), often used to assess both mobility, and static and dynamic balance, was used in two of the articles (Orssatto et al., 2018; Naderi et al., 2021) alongside other measures of performance.

Studies that assessed function of the elbow flexors tended to report larger decreases in strength than those that assessed function of the lower limbs. For example, decreases in elbow flexor MVC after exercise ranged from 42-49 % (Dedrick & Clarkson, 1990; Lavender & Nosaka, 2007), whilst decreases in plantar flexor and knee extensor strength ranged from 9-36 % (Ferri et al., 2006; Naderi et al., 2021). Of the four studies that measured elbow flexor strength (Dedrick & Clarkson, 1990; A. P. Lavender & Nosaka, 2006; Andrew P. Lavender & Nosaka, 2006; Lavender & Nosaka, 2007), three were conducted by the same research group using the same exercise protocol (A. P. Lavender & Nosaka, 2006; Andrew P. Lavender & Nosaka, 2006; Lavender & Nosaka, 2007). Time to complete the TUG test varied between the two studies, with one reporting a 2 % increase in time (Orssatto et al., 2018), and the other 18 % (Naderi et al., 2021). Declines in muscle function tended to peak from 0 to 48-hours, and in most studies took over 72-hours to fully recover. In some instances, the total length of the study was not long enough to record total recovery of physical functioning.

Of the four articles identified that involved a repeated bout within their protocol, three of the four suggested a protective effect of repeated exercise (Ploutz-Snyder et al., 2001; Chen et al., 2013; Škarabot et al., 2019), whereas one study found it did not significantly lessen decreases in MVC (A. P. Lavender & Nosaka, 2006).

Muscle Soreness

Nine studies were identified that measured muscle soreness (pain) following resistance exercise (Table 2.5). Of these nine studies, seven involved eccentric exercise (Clarkson & Dedrick, 1988; Dedrick & Clarkson, 1990; Andrew P. Lavender & Nosaka, 2006; A. P. Lavender & Nosaka, 2006; Chen et al., 2013; Buford et al., 2014; Sorensen et al., 2018), seven included a younger group for comparison (Clarkson & Dedrick, 1988; Dedrick & Clarkson, 1990; Andrew P. Lavender & Nosaka, 2006; A. P. Lavender & Nosaka, 2006; Buford et al., 2014; Nikolaidis, 2017; Sorensen et al., 2018), and five included females in the sample (Clarkson & Dedrick, 1988; Dedrick & Clarkson, 1990; Buford et al., 2014; Sorensen et al., 2018; Naderi et al., 2021). All of the included studies used a visual analogue scale (VAS) to assess perceived muscle soreness in the exercised limb. Due to slight discrepancies in the scales used to assess perceived soreness, it is difficult to provide an absolute value for the magnitude of change, but the identified studies all appear to report only mild increases in soreness. Several studies reported that perceived muscle soreness was significantly lower in older adults when compared with a younger group (A. P. Lavender & Nosaka, 2006; Andrew P. Lavender & Nosaka, 2006; Buford et al., 2014), whilst others report no effect of age (Clarkson & Dedrick, 1988; Dedrick & Clarkson, 1990; Sorensen et al., 2018). Muscle soreness in older adults appears to peak at 24-48 hours following damaging exercise, and is largely recovered 3-5 days following exercise. Two studies provided evidence for reduced soreness after repeated exercise bouts (Clarkson & Dedrick, 1988; Chen et al., 2013), and one study found that both massage and cold-water immersion could reduce soreness ratings 48-hours after exercise (Naderi et al., 2021).

Table 2.4 Studies Reporting Physical Function

Study	Subjects	Age (years)	Exercise	Time points	Marker	Results			
						Time to peak	Magnitude of change	Time to recovery	Other findings
Dedrick & Clarkson (1990)	20 healthy females (10 young, 10 older)	24 ± 3, 67 ± 5	24 reps eccentric contractions of elbow flexors @115% maximal isometric strength	Baseline, 24-, 48-, 72-, 96-, 120-h	MIVC elbow flexor	24 - 48-h	↓12 Nm (42 %)*#	Not recovered	
Ploutz-Snyder et al. (2001)	12 healthy females (6 young, 6 older)	23 ± 4, 66 ± 5	10 x 10 reps unilateral eccentric contractions of knee extensors @75% eccentric 1-RM	Baseline, 24-, 72-, 96-, 168-, 216-, 264-h	1-RM CON	24-h	↓24 %*	168-h	Strength deficit after RT reduced after 12-wks training
					1-RM ECC	24-h	↓27 %*	72-h	
Ferri et al. (2006)	9 healthy males	72 ± 4	10 x 10 reps seated calf raises @70% 1-RM	Baseline, 1-, 48-, 96-, 144-h	MIVC ankle flexor	N/A	↔	N/A	Neuromuscular fatigue not exercise induced muscle damage
					Maximal voluntary torque at;				
					-60^{o} s^{-1}	1-h	↓ 8.4 Nm (9 %)*	24-h	
					60^{o} s^{-1}	N/A	↔	N/A	
					120^{o} s^{-1}	1-h	↓ 4.5 Nm (16 %)*	24-h	
Lavender & Nosaka (2006a) May APNM	20 healthy males (10 young, 10 older)	19 ± 0, 71 ± 2	6 x 5 reps eccentric contractions of elbow flexors @40% maximal isometric strength	Baseline, 0-, 1-, 24-, 48-, 72-, 96-, 120-,	MIVC elbow flexor	0-h	↓48 %*#	Not recovered	MIVC was 87 % of baseline values at 10-d

				168-, 240-h					
Lavender & Nosaka (2006b) June EJAP	18 healthy males (10 young, 8 older)	20 ± 2, 71 ± 4	6 x 5 reps eccentric contractions of elbow flexors @40% maximal isometric strength	Baseline, 0-, 24-, 48-, 72-, 96-h	MIVC elbow flexor	0-h	↓48 %*#	Not recovered	Repeated bout did not significantly attenuate decreases in MIVC
Lavender & Nosaka (2007)	32 healthy males (10 young, 12 middle-aged, 10 older)	20 ± 2, 48 ± 7, 71 ± 4	6 x 5 reps eccentric contractions of elbow flexors @40% maximal isometric strength	Baseline, 0-, 24-, 48-, 72-, 96-, 120-h	MIVC elbow flexor	0-h	↓49 %*#	Not recovered	Ageing does not affect force fluctuations before or after eccentric exercise
Chen et al. (2013)	26 healthy males	66 ± 5	6 x 10 reps maximal eccentric contractions of knee extensors	Baseline, 0-, 24-, 48-, 72-, 96-, 120-h	MVC-CON 30^{o} s^{-1} knee extensors	0-h	↓28 %*#	Not recovered	Low intensity eccentric bout 7-d prior reduced deficits in MVC
Buford et al. (2014)	30 healthy adults (15 young, 15 older). Each group 5 females, 5 males.	23 ± 4, 76 ± 5	150 reps unilateral eccentric contractions of plantar flexors @110% 1-RM	Baseline, 48-, 168-h	Maximal voluntary torque plantar flexors	48-h	↓20 Nm (14 %)#	Not recovered	Old and young similar
Nikolaidis et al. (2017)	20 healthy males (10 young, 10 older)	22 ± 4, 67 ± 5	5 x 15 reps of back squat @75 % 1-RM on a smith machine	Baseline, 48-h	MIVC knee extensors	N/A	↓31 Nm (-23 %)*#	N/A	
Orssatto et al. (2018)	22 healthy adults. 7 females, 15 males. Two groups.	66 ± 5, 67 ± 5	3 x failure @70 % or @95 % 5-RM of leg press and leg curl	Baseline, 0-, 24-, 48-, 72-h	Maximal voluntary peak torque knee extensors	0-h	↓14 %*# (G70) ↓17 %*# (G95)	24-h Not recovered	Groups are 70% 5RM, and 95% 5RM
					Timed up and go	0-h	↑ 2%*# (G70) ↑ 6%*# (G95)	24-h 24-h	

					CMJ			24-h	
						0-h	↓8 %*# (G70) ↓11%*# (G90)	24-h	
					Stair Ascent			Not recovered	
						72-h	↑6 %*# (G70)	Not recovered	
							↑4%*# (G95)	N/A	
					Stair Descent	N/A	↔		
Sorensen et al. (2018)	19 healthy adults (11 young, 8 older). 4 females in young group.	22 ± 2, 71 ± 7	300 reps maximal eccentric contractions of the knee extensors	Baseline, 24-, 72-h	MVC-CON 60^{0} s-1 knee extensors	0-h	↓34 %*#	72-h	Unable to recruit older women able to perform exercise
					Peak isokinetic power	0-h	↓35 %*#	24-h	
Marques et al. (2019)	31 institutionalized adults. 14 males, 17 females.	79 ± 7	2 or 4 sets of 5 CMJ. 3 sets of 6 or 12 reps 2 kg SMBT (seated medicine ball throw). 3 sets of 8 or 15 reps of leg-press and chest-press @65 % 1-RM 3 sets of 6 or 12 reps 5 kg chair-squat	Baseline, 5-min	SMBT	N/A	↔ low volume ↓3 %* high volume	N/A	
					CMJ	N/A	↓5 % low volume ↓ 8 %* high volume	N/A	
					Hand-grip strength	N/A	↑3 %* low volume ↓1 % high volume	N/A	
Skarabot et al. (2019)	33 healthy adults (12 young, 11 older). 2 and 3 females respectively	27 ± 5, 66 ± 4	10 sets of 6 reps maximal eccentric contractions of dorsi-flexions	Baseline, 0-, 24-, 72-h	MIVC knee extensors	0-h	↓ 22 %*	72-h	Repeated bout protective

Naderi et al. (2021)	78 healthy adults	66 ± 3	4 sets of 10 reps of 3 exercises (standing calf raise with DB, standing and seated calf raise with machine) @75% 1-RM	Baseline, 24-, 48-, 72-h	MVC-CON 60^{o} s^{-1} plantar flexors	48-h	↓12 Nm (36 %)*#	Not recovered	Massage attenuated declines in strength and TUG
					Timed up and go	48-h	↑2 s (18 %)*#	Not recovered	

data extracted from figures, * significantly different from baseline, 1-RM one-repetition maximum, 5-RM five repetition maximum, DB dumbbell, CMJ countermovement jump, SMBT seated medicine ball throw, MIVC maximal isometric voluntary contraction, CK creatine kinase, Mb myoglobin, CON concentric, ECC Eccentric, h hours, d days, wks weeks, RT resistance training, ↑ increase, ↓ decrease, ↔ no change.

Table 2.5 Studies Reporting Perceived Muscle Soreness

Study	Subjects	Age (years)	Exercise	Time points	Scale	Results			
						Time to peak	Magnitude of change	Time to Recover	Other findings
Clarkson & Dedrick (1988)	20 healthy females (10 young, 10 older)	24 ± 3, 67 ± 5	24 reps eccentric contractions of elbow flexors @115% maximal isometric strength	Baseline, 24-, 48-, 72-, 96-, 120-h	1 (no pain) to 10 (very painful)	48-h	↑3 points*#	72-h	Older peaked 24-h after young. Repeated bout (7-d) reduced pain rating
Dedrick & Clarkson (1990)	20 healthy females (10 young, 10 older)	24 ± 3, 67 ± 5	24 reps eccentric contractions of elbow flexors @115% maximal isometric strength	Baseline, 24-, 48-, 72-, 96-, 120-h	1 (no pain) to 10 (very painful)	48-h	↑2 points*#	96-h	Older peaked 24-h after young
Lavender & Nosaka (2006a) May APNM	20 healthy males (10 young, 10 older)	19 ± 0, 71 ± 2	6 x 5 reps eccentric contractions of elbow flexors @40% maximal isometric strength	Baseline, 0-, 24-, 48-, 72-, 96-, 120-, 144-, 168-h	VAS: 0 (no pain) to 50 (extreme pain) mm	24-48-h	↑19 mm*#	120-h	Older had smaller increase compared with young.
Lavender & Nosaka (2006b) June EJAP	18 healthy males (10 young, 8 older)	20 ± 2, 71 ± 4	6 x 5 reps eccentric contractions of elbow flexors @40% maximal isometric strength	Baseline, 0-, 24-, 48-, 72-, 96-h	VAS: 0 (no pain) to 50 (extreme pain) mm	24-48-h	↑15mm*#	96-h	Older had smaller increase compared with young. Repeated bout effect more prominent in young.
Chen et al. (2013)	26 healthy males	66 ± 5	6 x 10 reps maximal eccentric contractions of knee extensors	Baseline, 0-, 24-, 48-, 72-, 96-, 120-h	VAS: 0 (not sore at all) to 100 (very, very sore) mm	48-h	↑12mm*#	72-h	Performance of sub-maximal exercise 7-d prior reduced soreness by 6-mm at 48-h
Buford et al. (2014)	30 healthy adults (15 young, 15 older). Each	23 ± 4, 76 ± 5	150 reps unilateral eccentric contractions	Baseline, 48-, 168-h	VAS: 0 (no soreness) to 100	48-h	↑28 mm*#	168-h	Older had smaller increase

	group 5 females, 5 males.		of plantar flexors @110% 1-RM		(extreme soreness) mm			compared with young.
Nikolaidis (2017)	20 healthy males (10 young, 10 older)	22 ± 4, 67 ± 5	5 x 15 reps of back squat @75 % 1-RM on a smith machine	Baseline, 48-h	1 (normal) to 10 (very sore)	N/A	↑ 6 points*#	N/A	
Sorensen et al. (2018)	19 healthy adults (11 young, 8 older). 4 females in young group.	22 ± 2, 71 ± 7	300 reps maximal eccentric contractions of the knee extensors	Baseline, 24-, 72-h	VAS: 0 (no pain) to 100 (unbearable pain) mm	24-h	↑ 30mm*#	Not recovered	No significant difference between young and old
Naderi et al. (2021)	78 healthy adults	66 ± 3	4 sets of 10 reps of 3 exercises (standing calf raise with DB, standing and seated calf raise with machine) @75% 1-RM	Baseline, 24-, 48-, 72-h	VAS: 0 (no pain) to 100 (extreme pain) mm	48-h	↑ 49 mm (passive recovery)*#	Not recovered	Both massage and cold water immersion after exercise reduced soreness by 10-mm at 48-h

data extracted from figures, * significantly different from baseline, 1-RM one-repetition maximum, reps repetitions, DB dumbbell, VAS visual analogue scale, h hours, d days, ↑ increase.

Risk of Falls

Only two studies assessed balance and fall risk after an acute bout of resistance exercise in older adults (Moore et al., 2005; Naderi et al., 2021)(Table 2.6). Both studies included male and female participants and performed concentric resistance exercise of the lower limbs. Moore et al. (2005) (Moore et al., 2005) measured postural stability before and immediately after resistance exercise. The most recent study from Naderi et al. (2021) provides data on three variables that are useful for assessing falls risk every 24-hours for 72-hours after resistance exercise of the plantar flexors. These variables include centre of pressure (COP) sway, joint ankle position error, and fear of falling (Naderi et al., 2021). The peak change in all three variables was statistically significant compared with baseline and was observed at 48-hours after exercise, indicating a potentially increased risk of falls. This study also demonstrated that massage could attenuate increases in indicators of fall risk following muscle damaging exercise. Specifically, massage significantly reduced COP sway at 48-72 hours, joint position error at 24-, 48-, and 72- hours, and fear of falling at 24- and 72- hours compared with passive recovery. In contrast, cold water immersion was found only to improve fear of falling at 72-hours when compared with passive recovery.

2.4.4 Biological Markers of Muscle Damage

Circulating Muscle Proteins

Thirteen studies reported the acute effect of resistance exercise on circulating muscle proteins (Table 2.7). Three of these studies were conducted exclusively in females (Clarkson & Dedrick, 1988; Funghetto et al., 2013; Tajra et al., 2014), seven were conducted in males (Andrew P. Lavender & Nosaka, 2006; A. P. Lavender & Nosaka, 2006; Ferri et al., 2006; Chen et al., 2013; Nikolaidis, 2017; Cornish et al., 2018; Pereira et al., 2019), and three were conducted with a mixed sample (Thalacker-Mercer et al., 2010; Buford et al., 2014; Škarabot et al., 2019). Seven of the studies included a younger group of adults for comparison (Clarkson & Dedrick, 1988; Andrew P. Lavender & Nosaka, 2006; A. P. Lavender & Nosaka, 2006; Thalacker-Mercer et al., 2010; Buford et al., 2014; Nikolaidis, 2017; Škarabot et al., 2019). Nine of the studies involved an eccentric exercise protocol (Clarkson & Dedrick, 1988; Andrew P. Lavender & Nosaka, 2006; A. P. Lavender & Nosaka, 2006; Chen et al., 2013; Funghetto et al., 2013; Buford et al., 2014; Tajra et al., 2014; Pereira et al., 2019; Škarabot et al., 2019), three of which were solely using elbow flexors (Clarkson & Dedrick, 1988; Andrew P. Lavender & Nosaka, 2006; A. P. Lavender & Nosaka, 2006), one used an eccentric-concentric protocol of the knee extensors (Thalacker-Mercer et al., 2010), and the remainder used concentric protocols involving the whole body or lower limbs (Ferri et al., 2006; Funghetto et al., 2013; Tajra et al., 2014; Nikolaidis, 2017; Cornish et al., 2018).

CK was the mostly widely reported circulating muscle protein, being reported as a marker of muscle damage in 12/13 studies. Time to peak concentration of CK ranged from 24-120 hours, and was not recovered in the studies, with the exception of Ferri et al (2006), where CK returned to baseline at 96-hours. The magnitude of increase of CK after exercise ranged from 46 % (Thalacker-Mercer et al., 2010) to 1641 % (A. P. Lavender & Nosaka, 2006) increase from baseline values.

Myoglobin (Mb) levels after resistance exercise in older adults were reported in five studies, with the studies reporting peaks from 1-hour (Ferri et al., 2006), to 120-hours (Andrew P. Lavender & Nosaka, 2006). The increase of Mb ranged from 73 % (Ferri et al., 2006), to 824 % (A. P. Lavender & Nosaka, 2006). One study did not provide a baseline value for Mb, and so an absolute or relative increase could not be calculated (Andrew P. Lavender & Nosaka, 2006). Lactate dehydrogenase (LDH) was reported by one study (Ferri et al., 2006) where it reached a peak increase of 17 IU/L (5 %) at 48-hours, and was recovered to baseline by 96-hours.

Table 2.6 Studies Reporting Risk of Falls

Study	Subjects	Age (years)	Exercise	Time-Points	Outcome Measure	Effect on Falls Risk	Other findings
Moore et al. (2005)	21 healthy adults. 5 males, 16 females	71 ± 4	10-12 reps each of knee extension, ankle dorsiflexion, ankle plantar flexion, hip abduction, knee flexion	Baseline, 0-h	Diffusion co-efficient analysis	↔	
					Critical point analysis	↑*	
Naderi et al. (2021)	78 healthy adults	66 ± 3	4 sets of 10 reps of 3 exercises (standing calf raise with DB, standing and seated calf raise with machine) @75% 1-RM	Baseline, 24-, 48-, 72-h	COP Sway	↑ 45 % (48-h)*	Massage reduced COP sway at 48-72-h
					Ankle joint position error	↑ 81 % (48-h)*	Massage reduced joint position error at 24-, 48-, and 72-h
					Fear of falling	↑ 27 % (48-h)*	Massage improved fear of falling at 24- and 72-h. Cold water immersion improved fear of falling at 72-h

data extracted from figures, * significantly different from baseline, 1-RM one-repetition maximum, reps repetitions, COP centre of pressure, DB dumbbells, h hours, ↑ increase, ↔ no change.

Table 2.7 Studies Reporting Circulating Muscle Proteins

Study	Subjects	Age (years)	Exercise	Time points	Marker	Results			
						Time to peak	Magnitude of change	Time to recovery	Other findings
Clarkson & Dedrick (1988)	20 healthy females (10 young, 10 older)	24 ± 3, 67 ± 5	24 reps eccentric contractions of elbow flexors @115% maximal isometric strength	Baseline, 24-, 48-, 72-, 96-, 120-h	CK	120-h	↑180 IU/L (273 %)*#	Not recovered	
Ferri et al. (2006)	9 healthy males	72 ± 4	10 x 10 reps seated calf raises @70% 1-RM	Baseline, 1-, 48-, 96-, 144-h	CK	48-h	↑52 U/L (60.3%)*	96-h	
							↑19 U/L (73.2%)*		
					Mb	1-h		48-h	
							↑17 U/L (5.3%)*		
					LDH	48-h		96-h	
Lavender & Nosaka (2006a) May APNM	20 healthy males (10 young, 10 older)	19 ± 0, 71 ± 2	6 x 5 reps eccentric contractions of elbow flexors @40% maximal isometric strength	Baseline, 0-, 24-, 48-, 72-, 96-, 120-, 144-, 168-h	CK	96 - 120-h	↑ 1996 IU/L (1358 %)*# Baseline not given*	Not given	Peak CK and Mb higher in young
					Mb	96 - 120-h		Not given	
Lavender & Nosaka (2006b) June EJAP	18 healthy males (10 young, 8 older)	20 ± 2, 71 ± 4	6 x 5 reps eccentric contractions of elbow flexors @40% maximal isometric strength	Baseline, 0-, 24-, 48-, 72-, 96-h	CK	96-h	↑1657 IU/L (1641 %)*#	Not recovered	Increases in CK and Mb higher in young. Repeated bout significantly attenuated increases in Mb
					Mb	96-h	↑ 406 ng/ml (824 %)*#	Not recovered	
Thalacker-Mercer et al. (2010)	39 healthy adults (19 younger, 20 older)	37 ± 1, 73 ± 1	9 x 10 reps bilateral, concentric-eccentric knee extension @40% MIVC	Baseline, 24-h	CK	N/A	↑54 U/L (46 %)*	Not recovered	

Chen et al. (2013)	26 healthy males	66 ± 5	6 x 10 reps maximal eccentric contractions of knee extensors	Baseline, 0-, 24-, 48-, 72-, 96-, 120-h	CK Mb	96-h 96-h	↑1473 IU/L (1009 %)*# ↑254 ug/L (726 %)*#	Not recovered	Previous sub-max exercise significantly attenuated increases in CK and Mb
Funghetto et al. (2013)	90 obese females	69 ± 6	7 x 10 reps eccentric bilateral knee extension isoinertial machine with a load corresponding to 110% of 10RM	Baseline, 0-, 3-, 24-, 48-h	CK	24 - 48-h	↑39- 47 IU/L (42-44%)*	Not recovered	Only GG allele group had a peak significantly higher than baseline
Buford et al. (2014)	30 healthy adults (15 young, 15 older). Each group 5 females, 5 males.	23 ± 4, 76 ± 5	150 reps unilateral eccentric contractions of plantar flexors @110% 1-RM	Baseline, 48-, 168-h	CK	48-h	↑0.14 (log) IU/L	Not recovered	Older peaked later than young
Tajra et al. (2014)	90 obese females	69 ± 6	7 x 10 reps eccentric bilateral knee extension isoinertial machine with a load corresponding to 110% of 10RM	Baseline, 0-, 3-, 24-, 48-h	CK	48-h	↔ (non-responders) ↑ 202 U/L (157 %)*# (high responders)	N/A Not recovered	Evidence for high and low responders to CK
Nikolaidis (2017)	20 healthy males (10 young, 10 older)	22 ± 4, 67 ± 5	5 x 15 reps of back squat @75 % 1-RM on a smith machine	Baseline, 48-h	CK	N/A	↑1534 IU/L (1112 %)*#	N/A	No difference between young and older
Cornish et al. (2018)	11 healthy males	72 ± 5	144 reps at 60% 1-RM OR 120 reps at 72% 1-RM OR 108 reps at 80% 1-RM of chest press, shoulder press, seated row, leg	Baseline, 0-, 3-, 6-, 24- 48-h	Mb	3 - 6-h	↑20 ng/ml (96 %)*#	48-h	No effect of intensity on Mb

			press, leg extension, and plantar flexion					
Pereira et al. (2019)	28 healthy males	GG genotype: 71 ± 4 CC/CG genotype: 72 ± 4	10 x 7 reps of eccentric contractions of knee flexors and extensors	Baseline, 0-, 3-, 24-, 48-h	CK	24-h	↑85 U/L (57%)*#	Not recovered	No difference between genotypes
Skarabot et al. (2019)	33 healthy adults (12 young, 11 older). 2 and 3 females respectively	27 ± 5, 66 ± 4	10 x 6 reps maximal eccentric contractions of dorsi-flexions	Baseline, 0-, 24-, 72-h	CK	24-h	↑108 IU/L (111%)*	Not recovered	Repeated bout significantly attenuated increases in CK

data extracted from figures, * significantly different from baseline, 1-RM one-repetition maximum, reps repetitions, CK creatine kinase, Mb myoglobin, LDH lactate dehydrogenase, h hours, ↑ increase, ↔ no change.

Cytokines

Eleven studies investigated the effect of resistance exercise on the acute cytokine response in older adults (Table 2.8). The most common cytokine to be reported in the literature was Interleukin-6 (IL-6)(9/11 studies), followed by Tumor-necrosis-factor-α (TNF- α)(3/11), Interleukin-1β (IL-1β)(3/11), Interleukin-10 (IL-10) (2/11), and Interleukin-8 (IL-8) (2/11). Across all of the studies, both males and females were included, and the mean age of participants ranged from 68 to 76 years. Ten of the eleven studies performed exercise solely for the lower limbs, with one study using a whole-body exercise protocol.

In five of the nine studies that included IL-6 (Przybyla et al., 2006; Funghetto et al., 2013; Patterson et al., 2013; Sorensen et al., 2018; Pereira et al., 2019), no significant increases in the cytokine were observed following resistance exercise. In two of the remaining four studies, increases in IL-6 ranged from 26-28 %, at 24- (Thalacker-Mercer et al., 2010), and 6-hours (Cornish et al., 2018) respectively, whereas in another study, IL-6 mRNA increased 1662-6433 % 2-hours post-exercise (Mathers et al., 2012). Lastly, in one study on 90 obese females, participants were grouped as 'responders' and 'non-responders' (Tajra et al., 2014). 'Non-responders' within this study had no significant increase in IL-6 after exercise, whereas the 'responders' group saw significant increases of 210 % from baseline. In all of the studies that IL-6 was found to increase, baseline levels were restored before 48-hours.

No increases in TNF-α or IL-10 were observed after resistance exercise in older adults in any study. Jensen et al. (2020) reported a three-fold increase in IL-1β in men at 4.5-hours, which returned to baseline at 24-hours post resistance exercise (Jensen et al., 2020). No increases were observed in women within the same paper, although blood samples were only taken at 120-hours post-exercise in women, and they performed a different exercise protocol. No increases in IL-1β were observed in the other two of the three studies in which it was reported (Przybyla et al., 2006; Sorensen et al., 2018), when it was measured at 24- and 72-hours post-exercise. IL-8 increased by 29 pg/ml (1140 %) at 24-hours, and was not recovered at 72-hours in a study by Sorensen et al (2018)(Sorensen et al., 2018), but did not significantly increase in the study conducted by Thalacker-Mercer (2010)(Thalacker-Mercer et al., 2010). Other cytokines that were found to increase include monocyte chemoattractant protein-1 (MCP-1)(Sorensen et al., 2018), monokine induced by gamma (MIG) (Sorensen et al., 2018), interferon-gamma inducible protein 10kDa (IP-10) (Sorensen et al., 2018), interferoninducible T cell alpha chemoattractant (I-TAC) (Sorensen et al., 2018), and interleukin-1R (IL-1R)(Jensen et al., 2020).

Table 2.8 Studies Reporting Cytokine Response

Study	Subjects	Age (years)	Exercise	Time points	Marker	Results			
						Time to peak	Magnitude of change	Time to recovery	Other findings
Przybyla et al. (2006)(Przybyla et al., 2006)	34 healthy males (17 young, 17 older)	32 ± 7, 71 ± 5	3 x 8 reps of bilateral leg press, leg curl, and leg extension @80% 1-RM. Plus 4th set to failure.	Baseline, 72-h	IL-6 IL-1β IL-1RA IL-10 AMAC-1	N/A N/A N/A N/A N/A	↔ ↔ ↔ ↔ ↔	N/A N/A N/A N/A N/A	IL-1β, IL-10, IL-1RA significantly higher in older at rest, and IL-1β, IL-10, AMAC-1 increased two-fold in young but not older
Thalacker-Mercer et al. (2010)	39 healthy adults (20 younger, 19 older)	37 ± 1, 73 ± 1	9 x 10 reps bilateral, concentric-eccentric knee extension @40% MIVC	Baseline, 24-h	IL-6 IL-8 TNF-α	N/A N/A N/A	↑ 0.34 pg/ml (24%)* ↔ ↔	N/A N/A N/A	IL-6 was also the only cytokine to change in young
Mathers et al. (2012)	35 healthy adults (20 males, 15 females)	68 ± 1, 67 ± 2	3 x 12 reps of maximal isokinetic eccentric and concentric unilateral leg extension	Baseline, 2-h	IL-6 mRNA (men) IL-6 mRNA (men)	N/A N/A	↑ 0.193 AU (6433%)* ↑ 0.133 AU (1662%)*	N/A	Increased similarly in males and females
Funghetto et al. (2013)	90 obese females	69 ± 6	7 x 10 reps eccentric bilateral knee extension isoinertial machine with a load corresponding to 110% of 10RM	Baseline, 0-, 3-, 24-, 48-h	IL-6	N/A	↔	N/A	
Patterson et al. (2013)	7 healthy males	71 ± 7	5 sets of unilateral knee extensions @20% 1-RM to fatigue with or without blood	Baseline, 30-, 60-, 120-min	IL-6	N/A	↔	N/A	Blood flow restriction did not alter plasma IL-6

			flow restriction in a counterbalanced order					
Buford et al. (2014)	30 healthy adults (15 young, 15 older). Each group 5 females, 5 males.	23 ± 4, 76 ± 5	150 reps unilateral eccentric contractions of plantar flexors @110% 1-RM	Baseline, 48-, 168-h	TNF-α	N/A	↔	N/A	
Tajra et al. (2014)	90 obese females	69 ± 6	7 x 10 reps eccentric bilateral knee extension isoinertial machine with a load corresponding to 110% of 10RM	Baseline, 0-, 3-, 24-, 48-h	IL-6	0-h	↔ (non-responders) ↑ 7.80 pg/ml (210%)*# (high responders)	48-h	'Normal' responders saw no significant increase
Cornish et al. (2018)	11 healthy males	72 ± 5	144 reps at 60% 1-RM OR 120 reps at 72% 1-RM OR 108 reps at 80% 1-RM of chest press, shoulder press, seated row, leg press, leg extension, and plantar flexion	Baseline, 0-, 3-, 6-, 24- 48-h	IL-6	6-h	↑ 0.49 pg/ml (28 %)*#	24-h	RT intensity had no effect on IL-6 levels
Sorensen et al. (2018)	19 healthy adults (11 young, 8 older). 4 females in young group.	22 ± 2, 71 ± 7	300 reps maximal eccentric contractions of the knee extensors	Baseline, 24-, 72-h	IL-6 IL-1β MCP-1 MIG IP-10 I-TAC IL-7 IL-8 IL-13 GCSF	N/A N/A 24-h 24-h 24-h 24-h N/A 24-h N/A N/A	↔ ↔ ↑198 pg/ml (1191%)* ↑175 pg/ml (127%)* ↑195 pg/ml (1598%)* ↑63 pg/ml (322%)* ↔ ↑29 pg/ml (1140%)* ↔ ↔	N/A N/A Not recovered 72-h 72-h 72-h N/A Not recovered N/A N/A	

Pereira et al. (2019)	28 healthy males	GG genotype: 71 ± 4 CC/CG genotype: 72 ± 4	10 x 7 reps of eccentric contractions of knee flexors and extensors	Baseline, 0-, 3-, 24-, 48-h	IL-6	N/A	↔	N/A	
Jensen et al. (2020)	25 healthy males,	70 ± 7	Men: 5 x 12 reps (70% 1-RM) followed by 4 x 6 eccentric reps (110% 1 RM).	Men: Baseline, 4.5-, 24-, 96-, and 168-h	TNF-α IL-10 IL-1β IL-1R	N/A N/A 4.5-h 4.5-h	↔ ↔ ↑3.0-fold* ↑4.4-fold*	N/A N/A 24-h 24-h	*Values only given relative to baseline (gene expression)
	24 healthy females (12 young, 12 older)	23 ± 3, 74 ± 3	Women: 2x [4 x 12 reps (70% 1-RM) followed by 4 x 4 eccentric reps (110% 1-RM) of unilateral knee extension]	Women: Baseline, 120-h	TNF-α IL-10 IL-1β IL-1R	N/A N/A N/A N/A	↔ ↔ ↔ ↔	N/A N/A N/A N/A	

data extracted from figures, * significantly different from baseline, 1-RM one-repetition maximum, RT resistance training, IL interleukin, min minutes, h hours,↑ increase, ↔ no change.

Immune Cell Response

Five studies (mean age 68-74 years) investigated the acute immune cell response to resistance exercise in older adults (Table 2.9). One study exclusively included females (Neves et al., 2009), another males (Jensen et al., 2020), and three used a mixed sample (Przybyla et al., 2006; Mathers et al., 2012; Sorensen et al., 2019). Four studies used exercise protocols of the lower limbs (Przybyla et al., 2006; Mathers et al., 2012; Sorensen et al., 2019; Jensen et al., 2020), and one study used a whole body exercise protocol (Neves et al., 2009). Four of the five studies retrieved a muscle biopsy for immunohistochemistry (Przybyla et al., 2006; Sorensen et al., 2019; Jensen et al., 2020) and PCR analysis (Mathers et al., 2012), and the remaining study collected a blood sample (Neves et al., 2009).

In the one study in which they were analysed (Neves et al., 2009), no change in leukocytes were detected in older adults following resistance exercise, but lymphocytes did increase by 29-30 % at 3-hours, and had returned to baseline levels by 48-hours (Neves et al., 2009). No differences were detected in Mac-1 gene expression (Mathers et al., 2012), total macrophage content, pro-inflammatory macrophage content, or anti-inflammatory macrophage content (Przybyla et al., 2006) in two of the studies. In the other two studies that observed macrophage content, measures of total macrophage content (CD68+) peaked at 72-168-hours, with neither study seeing a return to baseline values (Sorensen et al., 2019; Jensen et al., 2020). Other markers of macrophage content have only increased in one study each, CD11b peaked at 24-hours (Sorensen et al., 2019), CD206+ peaked at 72-hours (Sorensen et al., 2019), and CD163+ peaked at 168-hours (Jensen et al., 2020), with none of the markers being observed to return to baseline values.

In the study by Jensen et al. (2020), the female participants had a biopsy taken only at 120-hours post-exercise, and so the immune cell response to resistance exercise cannot be mapped in this group for this review (Jensen et al., 2020). The study did, however, use a control leg and an exercise leg, and therefore data is available that indirectly assesses changes in macrophage expression after resistance exercise (Jensen et al., 2020).

Satellite Cells

Eight studies reported the response of satellite cells to resistance exercise in older adults (Table 2.10). Five of the studies exclusively used male participants (Dreyer et al., 2006; Snijders et al., 2014; Heisterberg et al., 2018; Snijders et al., 2018; Nederveen et al., 2020), and three included males and females (Walker et al., 2012; Buford et al., 2014; Sorensen et al., 2019). The mean ages of participants in these studies ranged from 70 (Walker et al., 2012) to 76 (Buford et al., 2014) years. Two studies used a whole body exercise protocol (Snijders et al., 2018; Nederveen et al., 2020), and the remaining six used exclusively lower limb exercises.

The most commonly reported outcome was the number of satellite cells per fibre, and this was often broken down in to the number of satellite cells per type I fibre, and per type II fibre. Following resistance exercise, the number of satellite cells per type I fibre increased by 36-44 % peaking at 24-48 hours. The number of satellite cells per type II fibres increased by 30 % in only one study (Snijders et al., 2014), and did not significantly change in the other two studies (Heisterberg et al., 2018; Snijders et al., 2018). When reported as the number of satellite cells per mm^2, an increase of 44 % was observed at 48-hours in type I fibres, and an increase of 35 % was seen at 72-hours in type II fibres (Snijders et al., 2014). When expressed as satellite cells per mm^3, there was no significant change from pre-exercise levels (Sorensen et al., 2019). Two studies reported the number of satellite cells per myonuclei after resistance exercise. One of these studies found an increase of 22 % in older males, and 146 % in older females at 24-hours, the other found a 50 % increase in a mixed population (Dreyer et al., 2006).

Table 2.9 Studies Reporting Immune Cell Response

Study	Subjects	Age (years)	Exercise	Time points	Sample Site	Marker	Results			
							Time to peak	Magnitude of change	Time to recovery	Other findings
Przybyla et al (2006)	34 healthy males (17 young, 17 older)	32 ± 7, 71 ± 5	3 x 8 reps of bilateral leg press, leg curl, and leg extension @80% 1-RM. Plus 4th set to failure.	Baseline, 72-h	Vastus Lateralis muscle biopsy	CD68+ CD11b+ CD163+ CD115+	N/A N/A N/A N/A	↔ ↔ ↔ Not detected	N/A N/A N/A N/A	Young had higher levels of CD68+ at rest CD11b and CD63 increased in young after exercise
Neves et al (2009)	15 healthy females	68 ± 4	2 x 13 reps @50% 1-RM OR 2 x 8 reps @80% 1-RM of 6 exercises using all major muscle groups OR No exercise control	Baseline, 0-, 3-, 48-h	Blood sample	Total leukocytes Total lymphocytes	N/A 3-h	↔ ↑670 cells/mm^3 (29%)* - 50% 1-RM ↑715 cells/mm3 (30%)* - 80% 1-RM	N/A 48-h	Intensity had no effect on leukocytes or lymphocytes
Mathers et al (2012)	35 healthy adults (20 males, 15 females)	68 ± 1, 67 ± 2	3 x 12 reps of maximal isokinetic eccentric and concentric unilateral leg extension	Baseline, 2-h	Vastus Lateralis muscle biopsy	Total macrophages (Mac-1 gene expression)	N/A	↔	N/A	Males had higher Mac-1 expression at rest compared with women
Sorensen et al (2019)	19 healthy adults (11 young, 8 older). 4 females in	22 ± 2, 71 ± 7	300 reps maximal eccentric contractions of	Baseline, 3-, 24-, 72-h	Vastus Lateralis muscle biopsy	CD68+ CD11b+	72-h 24-h	↑2903 cells/mm^3 (122%)*# ↑2458 cells/mm^3 (461%)*#	Not recovered Not recovered	Higher proportion of pro-inflammatory macrophages at 24-h in young.

	young group.		the knee extensors			CD206+	72-h	↑ 869 cells/mm^3 (27%)*#	Not recovered	Higher proportion of anti-inflammatory macrophages at all time points in older
Jensen et al (2020)	25 healthy males	70 ± 7	Men: 5 x 12 reps (70% 1-RM) followed by 4 x 6 eccentric reps (110% 1 RM) eccentric contractions leg extension.	Men: Baseline, 4.5-, 24-, 96-, and 168-h	Vastus Lateralis muscle biopsy	CD68	162-h	↑0.07 cells/fibre (162%)*#	Not recovered	Women only had biopsy taken on day 5, so there is no data to compare pre- and post- exercise
						CD163+	162-h	↑0.06 cells/fibre (248%)*#	Not recovered	
	24 healthy females (12 young, 12 older)	23 ± 3, 74 ± 3	Women: 2x [4 x 12 reps (70% 1-RM) followed by 4 x 4 eccentric reps (110% 1-RM) of unilateral knee extension]	Women: Baseline, 120-h	Vastus Lateralis Muscle biopsy	CD68+ CD68+CD206+ CD68+CD11b+ CD68+CD11b+CD206 CD11b	N/A N/A N/A N/A N/A	N/A N/A N/A N/A N/A	N/A N/A N/A N/A N/A	

data extracted from figures, * significantly different from baseline, 1-RM one-repetition maximum, h hours, reps repetitions, ↑ increase, ↔ no change.

Table 2.10 Studies Reporting Satellite Cell Response

Study	Subjects	Age (years)	Exercise	Time points	Marker	Results			
						Time to peak	Magnitude of change	Comparison to young group	Other findings
Dreyer et al. (2006)	19 healthy males (10 young, 9 older)	60-75	12 reps, followed by 5 x 16 reps of single-leg maximal eccentric isokinetic loading of the knee extensors	Baseline, 24-h	SC/ fibre % SC (SC/ myonuclei)	N/A N/A	↑0.03/ fibre (51 %)* ↑1.31 (50 %)*	Young ↑ 417%* Young ↑ 119 %*	No difference between groups for baseline SC number
Walker et al. (2012)	21 healthy adults (10 young, 11 older). Each group had 5 females.	27 ± 2, 70 ± 2	8 x 10 reps of bilateral leg extension exercise @70% 1-RM	Baseline, 6-, 24-h	SC/ fibre % SC (SC/ myonuclei)	N/A 24-h	↔ ↑0.97 (22 %)* - males ↑ 3.17 (146 %)* - females	Only young males ↑ Young ↑ 148 %* Young ↑ 64 %*	
Buford et al. (2014)	30 healthy adults (15 young, 15 older). Each group 5 females, 5 males.	23 ± 4, 76 ± 5	150 reps unilateral eccentric contractions of plantar flexors @110% 1-RM	Baseline, 48-, 168-h	Pax7+ cells/ fibre	48 – 168-h	↑ 0.8/fibre (25 %)*#	No difference	
Snijders et al. (2014)	20 healthy males (10 young, 10 older)	22 ± 1, 73 ± 1	6 x 10 reps of horizontal leg press and leg extension @75% 1-RM	Baseline, 12-, 24-, 48-, 72-h	SC/ fibre (type I) SC/ fibre (type II) SC/ mm^2 (type I) SC/ mm2 (type II)	48-h 72-h 48-h 72-h	↑ 0.03/fibre (36 %)*# ↑ 0.02/fibre (30 %)*# ↑ 5.1/mm^2 (44 %)* ↑ 5.0/mm^2 (35 %)*	Young ↑ 52 %*# Young ↑ 55 %*# Young ↑ 41 %* Young ↑ 45 %*	SC/ fibre (type II) significantly lower in older at baseline, but no difference in type I

Heisterberg et al. (2018)	13 healthy males (placebo group)	71 ± 9	5 x 12 concentric reps @70% 1-RM and 4 x 6 eccentric reps @110% 1-RM unilateral leg extension	-240-, -72-, 4.5-, 24-, 96-, 168-h	SC/ fibre (type I)	N/A	↑ 0.014/ fibre (40 %)*#		Trend for SC to peak at 168-h in type I, and 24-h in type II but not significant
					SC/ fibre (type II)	N/A	↔		
Snijders et al. (2018)	27 healthy males	73 ± 1	3 x 10 reps @65% 1-RM leg press, chest press, horizontal row, and leg extension	Baseline, 24-, 48-h	SC/ fibre (type I)	24-h	↑ 0.04/ fibre (44 %)*#		
					SC/ fibre (type II)	N/A	↔		
Sorensen et al. (2019)	19 healthy adults (11 young, 8 older). 4 females in young group.	22 ± 2, 71 ± 7	300 reps maximal eccentric contractions of the knee extensors	Baseline, 3-, 24-, 72-h	SC/ mm^3	N/A	↔	Young ↑ 32 %	No difference in SC content between young and old pre-exercise
Nederveen et al. (2020)	24 healthy males	73 ± 1	4 x 10 reps each @65% 1 RM on leg press, chest press, horizontal row, and leg extension	Baseline, 24-, 72-h	%SC incarcerated	N/A	↔		Percentage of SC that are incarcerated after 12-wk exercise programme is reduced

data extracted from figures, * significantly different from baseline, 1-RM one-repetition maximum, reps repetitions, h hours, wk week, SC satellite cells, ↑ increase, ↔ no change.

2.4.5 Factors Influencing Recovery from Resistance Exercise

Effect of Exercise Intensity and Volume

Three studies have been identified that have investigated the effect of exercise intensity on markers of exercise-induced muscle damage in older adults (Neves et al., 2009; Cornish et al., 2018; Orssatto et al., 2018)(Table 2.11). Both males and females were included in these studies, with the mean age of participants ranging from 66 to 79 years. Two studies performed a whole body resistance exercise session (Neves et al., 2009; Cornish et al., 2018), whilst one study utilised just the lower limbs (Orssatto et al., 2018). All studies used a concentric exercise protocol. From this search, there does not appear to be any strong evidence that higher resistance exercise intensities cause greater muscle damage in older adults. Across the three studies, the only significant effect of intensity was observed by Orssatto et al. (Orssatto et al., 2018), who found that performing three sets to failure at 95% 5-RM, caused a greater magnitude of change in maximal isometric voluntary torque of the knee extensors than performing three sets to failure at 70% 5-RM. No significant effect has yet been found for the effect of resistance exercise intensity on leukocytes, lymphocytes, cytokine response, circulating muscle proteins, or any other measure of physical functioning.

One study was identified that reported the effect of exercise volume on markers of EIMD (Marques et al., 2019) in institutionalised older adults. Increasing exercise volume resulted in greater post-exercise decreases in counter-movement jump height and medicine ball throw distance.

Effect of Repeated Bout

Four studies were found that reported the effect of repeated bouts of exercise on muscle damage in older adults (Ploutz-Snyder et al., 2001; A. P. Lavender & Nosaka, 2006; Chen et al., 2013; Škarabot et al., 2019)(Table 2.12), including two studies in males (A. P. Lavender & Nosaka, 2006; Chen et al., 2013), one study in females (Ploutz-Snyder et al., 2001), and one in a mixed population (Škarabot et al., 2019). Time periods between exercise sessions ranged from one to four weeks (A. P. Lavender & Nosaka, 2006; Chen et al., 2013; Škarabot et al., 2019), with one study measuring muscle damage before and after a 12-week training programme (Ploutz-Snyder et al., 2001). All studies used an eccentric resistance exercise protocol. Both the upper and lower limbs have been studied, and a protective effect of a repeated bout on physical functioning has been observed in both. Across the studies, there is an almost unanimous finding that all markers of exercise induced muscle damage were reduced after performing a repeated bout of resistance exercise, with the only exception to this being no difference in creatine kinase levels between bouts in Lavender and Nosaka's 2006 study (A. P. Lavender & Nosaka, 2006). A repeated bout attenuated increases in creatine kinase in two other studies (Chen et al., 2013; Škarabot et al., 2019).

Recovery Strategies

One recent (2021) study was found to investigate exercise recovery strategies in older adults for up to 72-hours after resistance exercise (Naderi et al., 2021)(Table 2.13). The strategies employed in this study included cold water immersion and massage. Seventy-eight male and female participants that were not resistance trained, with a mean age of 66 years were included for analysis. The exercise consisted of a single bout of resistance exercise using the calf muscles across three exercises for four sets of ten repetitions at 75% 1-RM. A range of outcomes were measured including markers of physical functioning, muscle soreness, and risk of falls. Use of cold-water immersion had modest effects on reducing muscle soreness after exercise, but had limited benefits for improving physical functioning, joint position sense, balance, and fear of falling. In contrast, massage significantly attenuated symptoms of exercise induced muscle damage, and the related impairments in muscle strength and joint position sense when compared with passive recovery and cold-water immersion. Specifically, it was found that massage was effective for attenuating declines in MVC and the TUG test at 24-, 48-, and 72-hours following concentric exercise of the plantar flexors. Within the same study, cold water immersion was also found to attenuate deteriorations in the time to complete TUG test at 48-hours (Naderi et al., 2021).

There is currently no other literature assessing the effectiveness of any other recovery strategies for untrained older adults following a bout of resistance exercise.

Table 2.11 Studies Reporting the Effect of Exercise Intensity and Volume

Study	Subjects	Age (years)	Exercise Protocol 1	Exercise Protocol 2	Exercise Protocol 3	Main Outcomes	Effect of Higher Intensity On Magnitude of Change	Other findings
Neves et al. (2009)	15 healthy females	68 ± 4	2 x 13 reps @50% 1-RM	2 x 8 reps @80% 1-RM of 6 exercises using all major muscle groups	No exercise control	Total leukocytes	↔	
						Total lymphoctyes	↔	
Cornish et al. (2018)	11 healthy males	72 ± 5	144 reps @60% 1-RM of chest press, shoulder press, seated row, leg press, leg extension, and plantar flexion	120 reps @72% 1-RM of chest press, shoulder press, seated row, leg press, leg extension, and plantar flexion	108 reps @80% 1-RM of chest press, shoulder press, seated row, leg press, leg extension, and plantar flexion	IL -6	↔	
						Mb	↔	
Orssatto et al. (2018)	22 healthy adults. 7 females, 15 males. Two groups.	66 ± 5, 67 ± 5	3 x failure @70 % 5-RM of leg press and leg curl	3 x failure @95 % 5-RM of leg press and leg curl		Maximal voluntary peak torque knee extensors	↑*	
						Timed up and go	↔	
						CMJ	↔	
						Stair Ascent	↔	
						Stair Descent	↔	
Marques et al. (2019)	31 institutionalised adults. 14 males, 17 females.	79 ± 7	2 sets of 5 CMJ. 3 sets of 6 reps 2 kg SMBT (seated medicine ball throw). 3 sets of 8 reps of leg-press and chest-press @65 % 1-RM	4 sets of 5 CMJ 3 sets of 12 reps 2 kg SMBT (seated medicine ball throw) 3 sets of 15 reps of leg-press and chest-press @65 % 1-RM		CMJ	↑	*N.B Volume not intensity*
						SMBT	↑	
						Hand-grip strength	↓*	

	3 sets of 6 reps 5 kg chair-squat	3 sets of 12 reps 5 kg chair-squat	

* significantly different from baseline, 1-RM one-repetition maximum, 5-RM five-repetition maximum, CMJ countermovement jump, SMBT seated medicine ball throw, kg kilograms, MIVC maximal isometric voluntary contraction, IL-6 Interleukin-6, Mb Myoglobin, Con concentric, Ecc Eccentric, ↑ increase, ↓ decrease, ↔ no change.

Table 2.12 Studies Reporting the Effect of Repeated Bouts

Study	Subjects	Age (years)	Exercise	Intervention	Main Outcomes	Effect of Repeated Bout on Magnitude of Change	Other findings
Ploutz-Snyder et al (2001)	12 healthy females (6 young, 6 older)	23 ± 4, 66 ± 5	10 x 10 reps unilateral eccentric contractions of knee extensors @75% eccentric 1-RM	12-wk RT	Concentric 1-RM Eccentric 1-RM	↓* ↓*	
Lavender + Nosaka (2006b)	18 healthy males (10 young, 8 older)	20 ± 2, 71 ± 4	6 x 5 reps eccentric contractions of elbow flexors @40% maximal isometric strength	Replicate exercise at 4-wks	MIVC Muscle soreness CK Mb Range of motion Limb circumference	↓ ↓* ↔ ↓* ↓* ↓	Young had much greater repeated bout effect
Chen et al (2013)	26 healthy males	66 ± 5	6 x 10 reps maximal eccentric contractions of knee extensors	6 x 10 eccentric contractions @10% 1-RM 7-d prior	MVC Muscle soreness CK Mb Range of motion Limb circumference	↓* ↓* ↓* ↓* ↓* ↓*	No significant difference in any markers of damage following 10% 1-RM bout
Skarabot et al (2019)	33 healthy adults (12 young, 11 older). 2 and 3 females respectively	27 ± 5, 66 ± 4	10 x 6 reps maximal eccentric contractions of dorsi-flexions	Replicate exercise at 2-wks	MIVC CK	↓* ↓*	

* significantly different from baseline, 1-RM one-repetition maximum, MIVC maximal isometric voluntary contraction, CK creatine kinase, Mb myoglobin, d days, wks weeks, ↑ increase, ↓ decrease, ↔ no change.

Table 2.13 Studies Reporting Recovery Strategies

Study	Subjects	Exercise	Intervention	Main Outcomes	Time-points	Effect of Recovery Strategies on Magnitude of Change
Naderi et al. (2021)	78. Untrained healthy older adults >60 years old (age; 66±3 yrs). No RT experience <12 months)	Single bout RT on the calf muscles (3 exercises (standing calf raise with DB, standing and seated calf raise with machine) with 4 sets of 10 reps with 75% of 1-RM	Yes, Massage and cold water immersion (or passive recovery). Conducted <5min of variables being measured)	DOMS, fear of falling, TUG, COP, dynamic balance, joint position sense, Calf MVC.	Pre, 24-, 48- and 72-h.	Sway area COP increased 44.96 % in passive at 48-h. Massage reduced this at 48-72-h. Cold water immersion and massage reduced muscle pain at 48-h and 72-h compared with passive. Massage improved TUG at 24-h to 72-h compared with passive (CWI only improved at 48-h). Massage improved muscle strength compared with passive at 48-72-h. Massage improved fear of falling at 24-72-h. CWI improved only at 72-h compared with passive. Passive group had higher joint position error at 24-, 48- and 72-h compared with massage (also higher for CWI than massage at 24- and 72-h)

1-RM one-repetition maximum, RT resistance training, DB dumbbell, COP centre of pressure, TUG timed-up-and-go, DOMS delayed onset muscle soreness, MIVC maximal isometric voluntary contraction, DB dumbbell, CWI cold water immersion, h hours.

2.5 Discussion

2.5.1 Age Differences in Recovery from Resistance Exercise

The Effect of Age on Exercise-Induced Muscle Damage in Males

Despite the small number of studies, the data suggest that older males may experience less exercise-induced muscle damage than their younger counterparts, with six out of the seven studies reporting at least one variable that had a significantly smaller magnitude of change post-exercise in the older group. More specifically, muscle strength was significantly less reduced in the older group in every study that reported it (A. P. Lavender & Nosaka, 2006; Andrew P. Lavender & Nosaka, 2006; Lavender & Nosaka, 2007; Nikolaidis, 2017). No reported variable was significantly more changed in older adults' post-resistance exercise compared with younger adults. It is currently unclear why this may be the case, and there is no obvious underlying physiological mechanism at this time. Speculatively, this effect may stem from differences when performing exercise protocols such as older adults lifting less load, but there is little evidence for this thus far. The literature focussing on the time it takes older males to recover from resistance exercise is much less clear due to a full recovery of symptoms rarely being observed within the studies. For example, the study involving the longest follow up still did not see a full recovery of muscle strength at 240-hours post-exercise (Andrew P. Lavender & Nosaka, 2006). This lack of observed recovery is consistent across every study and almost every variable, with the exception of muscle soreness in two of the studies (A. P. Lavender & Nosaka, 2006; Andrew P. Lavender & Nosaka, 2006), and range of motion in one study (Andrew P. Lavender & Nosaka, 2006). This has implications for the prescription of training frequency and for exercise adherence, and should be taken into consideration when designing exercise interventions for older adults. Within these two studies, older males recovered muscle soreness and range of motion quicker than younger males, but this does not form strong enough evidence to suggest a differing recovery rate with age. The literature would therefore benefit from further tightly controlled studies which aim to understand the length of time it takes older males to recover from resistance exercise, rather than solely the effect of age on the magnitude of muscle damage. This review is not designed to make any conclusions regarding the effect of age on exercise induced muscle damage, and hence, a systematic review or meta-analyses will be needed following the publication of more controlled trials before conclusions can be drawn.

It should also be acknowledged that three of the seven studies used the same eccentric exercise protocol of the elbow flexors, and were published within a two year-period (A. P. Lavender & Nosaka, 2006; Andrew P. Lavender & Nosaka, 2006; Lavender & Nosaka, 2007). Whilst this is not an issue within itself, as it provides consistency within protocols, it should be considered when assessing the depth of the literature in this field. This is especially important as there is only one other study comparing physical function measures between young and older adults after resistance exercise. It is therefore difficult to deduce the effect that age has on time to fully recover from damaging resistance exercise.

The Effect of Age on Exercise-Induced Muscle Damage in Females

Due to the limited number of studies surrounding older females and exercise recovery, each marker of muscle damage has only ever been reported once in the literature. It is therefore difficult to draw conclusions on the effect of age on recovery in this population because of the lack of available data. However, initial data suggest that whilst age appears to convey some protection against exercise induced muscle damage in older males, the opposite may be true for older females. Previous work has suggested a protective effect of oestrogen on exercise-induced muscle damage (Dieli-Conwright et al., 2009; Thompson et al., 2020), which could provide an explanation for this trend. Indeed, oestrogen is typically much lower in older post-menopausal women than young women, and this reduction in hormone levels could explain the impaired exercise recovery rates in older women. Although this has not yet been investigated, a previous systematic review (Thompson et al., 2020) found five studies that reported markers of exercise-induced muscle damage in young females who were or were not taking oral contraceptives (Hicks et al., 2017; Minahan et al., 2015; Roth et al., 2001; Savage & Clarkson, 2002; Hayward et al., 1998). In the one study that endogenous oestrogen was higher prior to exercise in the oral contraceptive group, a lower CK response was reported post-exercise compared with the menstrual cycle group (Hayward et al., 1998), suggesting a potential protective effect of oestrogen on exercise-induced muscle damage. However, like the present review, no conclusions could be drawn due to a relatively small number of varied studies. Hence, it may be that different hormonal changes with age between sexes may be a greater determinant of how older adults recover from resistance exercise, rather than age itself. Indeed, it is currently unclear if sex is a determinant of exercise recovery in older adults, as little research has been done solely in males or females. Comparisons in exercise-induced muscle damage between males and females is also made difficult due to discrepancies in exercise protocols, the outcomes measured, and the length of the studies. More research should be done that seeks to directly compare male and female responses to resistance exercise, and more research is needed specifically in older females, to determine any effects of changing hormones on the exercise recovery process in older adults.

2.5.2 Symptoms of Exercise-Induced Muscle Damage

Physical Function

There is no clear consensus on the magnitude of the effect, or on the time it may take older adults to recover physical function after muscle damaging exercise. Both outcomes are relevant when designing training programs for previously untrained older adults. The lack of consensus within the literature on these variables likely stems from the variation in study protocols that have been highlighted by this review, mainly differences in the exercise protocols, the muscle groups investigated, and the time-points when measures have been collected. For example, time to complete the TUG test varied between the two studies that reported it, with one reporting a 2 % increase in time (Orssatto et al., 2018), and the other 18 % (Naderi et al., 2021). This is perhaps unsurprising given that different muscle groups were used across the two studies. Similarly, studies that assessed function of the elbow flexors tended to report larger decreases in strength than those that assessed function of the lower limbs. Decreases in elbow flexor MVC after exercise ranged from 42-49 %, whilst decreases in plantar flexor and knee extensor strength ranged from 9-36 %. This is not novel information, as the differences in the susceptibility of muscle groups to exercise induced muscle damage has previously been reported, with the upper limbs generally incurring more damage than the lower limbs, possibly due to muscle fibre characteristics and daily exposure to eccentrically biased actions (Chen et al., 2011; Jamurtas et al., 2005; Paschalis et al., 2010). However, this lack of consensus within the literature is not exclusively a result of differing muscle characteristics, but may also have been affected by exercise intensity, volume, individual characteristics of the participants, and study characteristics. Greater alignment of study protocols in the future, or a more considered approach of choosing an exercise protocol would be beneficial to determine the real-world effects of resistance exercise on older adults and allow more informed recommendations to be made. Indeed, it is unlikely that practitioners would prescribe a resistance exercise programme consisting of maximal eccentric contractions that are intended to cause maximal muscle damage. The outcome measures used to represent function are generally consistent, with 12 out of 14 studies measuring MIVC/MVC, a measure of muscular strength. However, when working with older adults, it may be wise to consider including additional measures of physical function which may be more clinically meaningful, such as fall risk or the TUG test, to ensure findings are applicable to the population.

Similarly, of the studies reporting physical function, few were of long enough duration to observe a convalescence of muscle strength and make recommendations for training frequency. It is unclear if this is due to a lack of ecological validity within the studies (i.e. the exercise bouts inducing much greater damage than would usually be observed in training), or if this is a reflection of the true time it takes older adults to recover. The longest study was 264-hours in duration, and recovery of concentric 1-RM was not observed until 168-hours (Ploutz-Snyder et al., 2001). However, not all studies observed full recovery. In a study that was 240-hours in duration, MVC of the elbow flexor after eccentric exercise was still not recovered to baseline by the end of the study (Andrew P. Lavender & Nosaka, 2006). Similarly, the next longest study had participants return at 168-hours, but maximal contraction of the plantar flexors was also not recovered at this time (Buford et al., 2014). In three of the studies (Ferri et al., 2006; Orssatto et al., 2018; Sorensen et al., 2018), peak decreases in function occurred immediately after exercise and function was recovered by 24-hours. It is likely that where a peak decrease in muscle function was recorded immediately after exercise, neuromuscular and metabolic fatigue were greater contributors than muscle damage at this time point. Large variation, a lack of studies that observe full recovery, and a lack of uniformity with time points for outcome measures means it is therefore unclear at exactly what rate older adults recover physical function. Without this information, it is difficult to recommend training frequencies or volumes that will both limit the negative consequences of exercise induced muscle damage and ensure optimal adaptation time in between exercise bouts. Additionally, if there is residual fatigue from previous exercise, it is likely that the quality of the training session could be affected, or adherence may be reduced. Hence, if older adults do take approximately a week to recover, practitioners may consider prescribing exercise in two- or three-weekly blocks rather than the traditional approach of weekly blocks to allow more time between sessions. Practitioners may also wish to consider adapting the volume or intensity of resistance exercise sessions, or adopting a body-part split approach, to ensure the physical activity guidelines of strength training two times per week are being met (UK Chief Medical Officers, 2019). Future studies seeking to characterise exercise recovery in older adults should look to extend the time that data is collected past 168-hours at the least, but may wish to consider extending beyond 240-hours. Focus should also be given to characterising the exercise recovery process in response to the various training variables that may be manipulated to ensure optimal exercise prescription for older adults.

Muscle Soreness

There is a considerable body of literature assessing the effect of resistance exercise on muscle soreness in older adults. The magnitude of change and time to peak change is relatively consistent across the studies, with all studies reporting peak changes at 24-48-hours. However, due to discrepancies in the visual analogue scales used, it is difficult to provide an absolute value for the magnitude of change. However, most studies assessing muscle soreness in older adults following resistance exercise reported only mild increases in soreness ratings, although it is unclear why this may be, and more work is needed to understand this.

There is some evidence that pain perception could decrease with ageing (Gibson & Helme, 2001) and thus, it is possible that the levels of muscle soreness within these studies have been under-reported. Indeed, three of the studies that compared muscle soreness with younger adults found that self-reported muscle soreness was significantly lower in the older group. In addition to a possible systemic under-reporting of soreness compared with younger adults, there is also large individual variation in the interpretation of the visual analogue scale (Kersten et al., 2014; Frey-Law et al., 2013). Caution should therefore be taken when analysing subjective muscle soreness, as it may only be useful when comparing intra-individual variation within a study, rather than drawing conclusions from absolute group values. Most of the studies reporting muscle soreness in older adults have used an eccentric exercise protocol, with only two using a concentric protocol. Whilst eccentric protocols are common practice to induce muscle damage for research purposes, it may not directly translate to the exercise sessions performed in a real-world setting, as they tend to cause greater soreness and damage (Clarkson & Sayers, 1999).

It has been suggested previously that older adults may be deterred from completing a resistance exercise programme if expectations that muscle soreness will be experienced are not set from the beginning (Hurst et al., 2022). The rationale being that they may confuse muscle soreness with injury or believe they will experience this soreness after every exercise bout. If the current data surrounding muscle soreness in older adults is accurate, and older adults have not under-reported soreness ratings, it is likely that soreness experienced from usual resistance exercise will be mild, especially if performing mainly concentric-based exercise protocols. Hence, it is unlikely that muscle soreness would prevent them from engaging in a structured resistance exercise programme. Nevertheless, DOMS is highly individual, and educating older adults prior to beginning an exercise programme may aid adherence in some older adults.

Falls Risk

There is a distinct lack of literature seeking to understand the acute effect of resistance exercise on falls risk in older adults. Despite there only being two studies within this area (Moore et al., 2005; Naderi et al., 2021), both indicate a potential detrimental effect on postural stability, which has long been associated with an increase in fall incidence (Fernie et al., 1982; Menant, Jasmine C and Okubo, Yoshiro and Menz, 2021). Similarly, several contributors to falls risk (e.g. muscle strength and power) are also compromised in the presence of exercise induced muscle damage. The earliest study provided evidence of decreased postural control after a single bout of resistance exercise using stabilogram-diffusion analysis (Moore et al., 2005), and the latest study, some 16 years later, showed an increase in COP sway area of 36 % after damaging exercise of the calf muscles (Naderi et al., 2021). Interestingly within the most recent study, fear of falling was also shown to increase after a bout of resistance exercise. Together the studies begin to provide important data regarding postural stability after resistance exercise in older adults. However, significant further research is needed within this area to fully understand the intricacies of how muscle damage and fatigue may affect falls risk.

Postural stability and the risk of falls is a significant topic in research, but so far there is very limited data on the effects of exercise on these parameters. The effects of resistance exercise on acute falls risk appears to be somewhat of a blind spot within the literature. It is possible that this is due the topic sitting within two historically separate fields of literature. Indeed, clinical research often does not go as far to produce research on the effects of exercise, whilst exercise science often does not consider the clinical implications of an exercise prescription for older adults. In an age where resistance exercise is being increasingly more commonly prescribed for older adults, this presents a pressing need for clinicians and exercise scientists to collaborate and ensure the best care for older generations.

2.5.3 Biological Markers of Muscle Damage

Circulating Muscle Proteins

The circulating muscle proteins that have been reported following resistance exercise in older adults are CK, myoglobin and lactate dehydrogenase. Potentially due to the relatively low cost of assays required for quantification, the most commonly reported of these is CK, with 12 of the 13 studies including the measure in their outcomes. However, there is no clear consensus across this literature on the magnitude of change or the temporal characteristics of CK post-exercise. This is similar to findings from research in younger adults post-exercise (Koch et al., 2014) where CK is also widely variable in both magnitude of change and the elapsed time to peak and recovery. When comparing the younger and older age groups, there is some evidence that CK increases to a greater extent in younger adults than older adults, but other studies show no difference between the groups.

The extent to which CK increases after exercise is dependent on individual factors, as well as environmental, and exercise variables (Koch et al., 2014; Hortobágyi & Denahan, 1989). The large variation of CK in studies across all age groups should be seen as a major limitation in exercise recovery research. Indeed, researchers should question whether assessing CK after exercise is an efficient use of resources, as often variation is too great to confer statistical significance between groups. Given the practical and ethical implications of collecting blood to measure CK, it should also be considered whether it is a useful measure. Whilst CK levels do generally increase after exercise-induced muscle damage, this is not always parallel to the magnitude of muscle fibre damage (Fridén & Lieber, 2001), and does not directly correlate to muscle function or other symptoms of exercise induced muscle damage that may be of more relevance to the individual (Baird et al., 2012). Hence, CK may be better used as a binary marker to determine the presence of exercise induced muscle damage or membrane disruption. It may be of greater use to the literature to focus on functional outcomes, or outcomes that may more directly inform the state of recovery when conducting research in older adults. The conclusions made for CK within this review also extend to myoglobin, but not to lactate dehydrogenase, where there is not enough data to determine if this measure is valid or reliable.

Cytokines

Similarly to circulating muscle proteins, there is no clear consensus on the effect of resistance exercise on the acute cytokine response in older adults despite numerous studies reporting this outcome. Interleukin-6 (IL-6), the major cytokine associated with the acute post-exercise inflammatory response (Steensberg et al., 2000) was the most commonly reported, and was generally a secondary outcome, but did not significantly increase in over half of the studies. Other cytokines that have been reported also do not reliably increase after resistance exercise in older adults. This finding appears to be similar for both inflammatory and anti-inflammatory cytokines. Due to the complexity of the overall post-exercise cytokine response, the non-specificity of cytokines to skeletal muscle, and the large inter-individual variability for each cytokine (Chow et al., 2022), it is unlikely that this is useful to measure when aiming to compare the exercise-induced muscle damage response amongst older adults. As cytokines are important mediators of chronic exercise-induced adaptations, it would be more pertinent to consider the effect of resistance exercise on these markers in older adults using specific, large scale studies. Studies that are designed to characterise symptoms of exercise-induced muscle damage, and where the sample size is likely not large enough to convey the required statistical power for assessing the cytokine response should refrain from including this outcome on both ethical, and practical grounds.

Immune Cell Response

There was no literature retrieved during this search that demonstrated an acute leukocyte response to resistance exercise in older adults, but there is a strong body of research in younger adults suggesting resistance exercise induces changes in leukocyte function and distribution (Freidenreich & Volek, 2012). This is similar to our findings for lymphocyte and macrophage responses.

It is possible that due to the search terms used in this scoping review focussing on exercise-induced muscle damage, some of the literature on the immune cell response after resistance exercise in older adults could have been overlooked. This is not to say that immune cell response to resistance exercise is not important, but it may carry less weight when using data to create practical guidelines for exercise in older adults. Again, researchers may wish to consider the significance of the immune response to their specific research aims and omit these measures if they will not impact their recommendations.

Satellite Cells

Satellite cells support skeletal muscle cell regeneration after damaging exercise, and hence, are relatively well-studied within the literature. However, as with the immune cell response, our search may not have identified all of the studies within this area. The most commonly reported outcome was the number of satellite cells per muscle fibre, with numbers found to increase from 36-44% in type I fibres. This increase was consistent across the studies, but was not as robust as the increases seen in younger adults. This finding would be consistent with the current consensus that ageing may reduce satellite cell populations, and reduce their repair capacity (Sousa-Victor et al., 2022). No studies in this review have been conducted solely in female participants, and hence, it is difficult to determine if these findings are consistent across sexes. As research suggests there may be sex differences in satellite cell number and response (Manzano et al., 2011; Song et al., 2013; Oxfeldt et al., 2022), future research should look to focus on the satellite cell response to resistance exercise in older women.

As satellite cell content is not necessarily directly correlated with the severity of exercise-induced muscle damage or recovery rate, the usefulness for acute (<72-h) exercise recovery literature may be limited. However, the satellite cell response to resistance exercise is still important for controlling skeletal muscle adaptation to exercise (Bruusgaard et al., 2010; Sousa-Victor et al., 2022), and so interventions that modify their response are likely to be beneficial within training programmes.

2.5.4 Factors Influencing Recovery from Resistance Exercise

Effect of Exercise Intensity and Volume

Performing resistance exercise at higher intensities can result in greater strength gains in older adults (Van Roie et al., 2013), but the effect of exercise intensity on muscle damage in older adults is understudied. Within this review, there is no clear evidence that higher intensities of resistance exercise cause greater muscle damage than lower intensities in older adults. A significant effect of exercise intensity on markers of muscle damage was found by one study, Orssatto et al. (Orssatto et al., 2018), but only on MVC, and not on any other measures of physical functioning. This study was the only study to investigate measures of physical functioning, and hence, more data is required before confirming an effect of exercise intensity. Currently, it is not possible to recommend exercise intensities with reference to minimizing temporary declines in physical function, and until more data is available, practitioners should base their recommendations on maximizing adaptation.

Only one study could be identified that assessed the effect of exercise volume on physical function measures during exercise recovery (Marques et al., 2019). Increased volume exacerbated the decrease in muscle function, and hence, may have an effect on the magnitude of muscle damage experienced after resistance exercise. However, as this is just one study, no conclusions can be made from this finding.

Effect of Repeated Bout

Performing repeated bouts of resistance exercise has consistently been shown to reduce the magnitude of muscle damage in older adults, despite the number of studies still being relatively limited. Across the four studies that have investigated the repeated bout effect, all of them reported a protective effect from muscle damage. This has implications for training prescription, as it is likely that exercise induced muscle damage will become less severe as individuals become accustomed to performing resistance exercise, and hence, perturbations in physical functioning may be of less concern. In practical terms, it may be possible that a lower volume or intensity training session in the first instance may act as a ‘buffer’ from muscle damage but more research is needed to verify the efficacy of this assumption. Similarly, more work is needed to determine whether the repeated bout effect is also present following concentric resistance exercise, as currently, there are no studies that have used this exercise protocol.

Recovery Strategies

There is currently only one study that reports the effect of recovery strategies on exercise induced muscle damage in older adults. These recovery strategies are massage and cold-water immersion. Both of these strategies show potential to decrease muscle damage, and expedite recovery, but massage appeared to have a greater effect. Whilst these results are interesting, the limited availability of any other study means these strategies cannot be recommended with any certainty until further studies have been conducted that include some variations in exercise prescription and participant characteristics.

There is currently no other literature assessing the effectiveness of any other recovery strategy for untrained older adults following a bout of resistance exercise. Alternative recovery strategies have been proposed, with nutrition gaining substantial traction in older trained adults, and younger adults alike (Davies et al., 2018; Clifford, 2019) but they are yet to be conducted within untrained older adults.

2.5.5 Strengths and Limitations

This is the first review that has aimed to comprehensively describe the current literature and identify priorities for future research surrounding recovery from resistance exercise in older adults. The previous review in this area excluded literature that did not include a younger comparison group (Fernandes et al., 2020), and hence, the inclusion of these studies in the present review allows for a more complete guide of the literature to be compiled. However, this is not a systematic review, and it is not designed to provide answers to specific research questions nor to assess the quality of the included studies. The findings from this chapter can therefore only be interpreted to be a summary of the wider literature, and cannot be used to characterise the exercise recovery process, or to define the effect of resistance exercise on individual markers of exercise induced muscle damage in older adults

2.6 Conclusions

Chronic adaptations to resistance exercise are well documented but the acute effects of resistance exercise, specifically the magnitude and time course of exercise induced muscle damage, in older adults are less clear. The process of exercise-induced muscle damage after resistance exercise is well-documented and extensively reviewed amongst younger adults, but original articles exploring this phenomenon in older adults are sparse. From the studies that have been conducted, it is hard to draw definitive conclusions about the effect of resistance exercise on physical functioning in the following days due to variations in study protocols and outcome reporting. Similarly, research into biological markers of muscle damage in older adults is limited and inconsistent, and their usefulness for assessing the magnitude of muscle damage should be considered. Research surrounding the presence of delayed onset muscle soreness in older adults is more consistent but still fails to answer why older individuals generally report less soreness than their younger counterparts. Across all measures of exercise induced muscle damage, data in females is lacking when compared with males, and rectifying this discrepancy should be a focus of future studies considering the large proportion of the population that this represents. A greater understanding of how resistance exercise affects function in the following days is essential to inform better exercise prescription, and the formation of suitable exercise recovery strategies for older adults.

Chapter 3 : Exploring What Older Adults Know about Exercise Recovery, Their Experiences of it, and Their Attitudes towards Exercise Recovery Interventions

3.1 Abstract

Aim

This chapter aimed to gather data on older adult's knowledge and attitudes towards resistance exercise, exercise recovery, and exercise recovery supplements. This chapter describes how older adults perceive resistance exercise and muscle damage, and how they may engage with exercise recovery strategies after recommended exercise training.

Methods

We sought the opinions of any individual over 70 years of age via an online survey. The survey collected both qualitative and quantitative data. This survey collected information on older adults' physical functioning, physical activity status, barriers and motivators for participating in resistance exercise, their knowledge and experiences of exercise recovery, and their attitudes towards exercise recovery interventions.

Results

We recruited 291 individuals (73.9 ± 3.7 years) for this survey, 95 % were fully independent and 25 % participated in resistance exercise. Physical health was both the most common motivator and barrier to resistance exercise, but education, social support, and accessibility were also deemed important. Older adults' knowledge of exercise recovery was limited, and experiencing muscle soreness may discourage them from completing further exercise. Whole foods were deemed to be more acceptable than supplements due to a negative perception of supplements. However, older adults' knowledge of exercise recovery strategies was limited.

Conclusions

There is a clear need for education on the benefits of resistance exercise for health in order to improve adherence to resistance exercise. Older adults would also benefit from further knowledge on the process of exercise recovery, and the role of nutrition for aiding exercise recovery.

3.2 Introduction

Despite a considerable body of literature demonstrating the benefits of resistance exercise in older adults (Steib et al., 2010; Borde et al., 2015a), the process of recovery from resistance exercise is largely understudied. More specifically, whilst there are a small number of studies that have aimed to investigate physiological differences in exercise recovery as we age, as far as we are aware, no literature has sought to define the knowledge and perspectives of older adults on matters surrounding exercise recovery. Similarly, despite nutrition, specifically cow's milk, quickly gaining traction as both an effective intervention to prevent sarcopenia, and for enhancing exercise recovery in younger populations, older adults' preferences for nutrition-based recovery strategies is distinctly understudied.

Continued uptake and adherence to resistance exercise programmes is essential for improvements in muscle strength and physical function (Dent et al., 2018; Hurst et al., 2022). However, these are dependent on an individual altering their behaviours. Understanding these sources of behaviour can aid in creating effective interventions (Michie et al., 2011). Hence, understanding the knowledge and views of the older population could allow us to tailor resistance exercise interventions and exercise recovery strategies, to promote adherence to, and improve the effectiveness of, exercise programmes.

One recent study explored older adults' attitudes and barriers to engaging in a resistance exercise program alongside consuming a recovery drink (cow's milk) after exercise (Dismore et al., 2020). Self-perceived health improvement, knowledge acquisition, social wellbeing, professional support, and a fun environment were all identified as motivators for engagement in the resistance exercise program. Affordability, concern over self-injury in the gym without practical support, and concerns over negative health outcomes were cited as barriers for continued participation. Just one participant expressed negative views of milk consumption due to the taste (skimmed milk condition), and only one reported an issue with the required liquid volume. The data collected suggested that older adults considered whole milk to be an acceptable post-exercise recovery drink. The findings of this study are limited to a relatively small number of healthy older adults that willingly participated in a health intervention, and hence, may not provide data representative of all community-dwelling older adults. We are aware of no other studies that have aimed to assess the acceptability of nutrition for exercise recovery in older adults.

To inform the direction of future research on this topic, it is important that researchers and practitioners alike understand what exercise recovery means to older adults regarding barriers and motivators to participation, willingness to train, and the acceptability of exercise recovery interventions. As such, this study aimed to understand the perspectives of community-dwelling older adults and determine their current knowledge of exercise recovery. To achieve this, this survey collected information on their physical functioning, their physical activity status, their barriers and motivators for participating in resistance exercise, their knowledge and experiences of exercise recovery, and their attitudes towards exercise recovery interventions such as cow's milk. This survey provides insights into how older adults perceive the exercise recovery process, and how they may engage in exercise recovery processes after recommended exercise training.

3.3 Methods

3.3.1 Ethical Approval

Ethical approval for this study was granted by Newcastle University Ethics Committee (Ref: 3648/2020). Before completing the survey, participants were given a brief overview of the purpose and aims of the study and were provided with contact details of the research team should they have had any questions. Participants were informed that by submitting their responses they were providing consent to participate in the questionnaire. Participants were able to withdraw at any time before submitting their responses by simply closing the tab on their web browser.

3.3.2 Participants

Participants were recruited through social media advertising (Facebook and Twitter), and patient and public involvement platforms (www.voice-global.org) during July-August 2020. Any individual over the age of 70 years with internet access could complete the survey - no other inclusion or exclusion criteria were applied.

3.3.3 Survey Design

This study used a mixed methods approach to investigate older adults' views. Specifically, it sought to explore older adults' knowledge, perceptions and experiences of recovery from resistance exercise. The online survey created aimed to gather data in five key areas; age and physical capability, physical activity status, barriers and motivations for participating in resistance exercise, knowledge of exercise recovery, and attitudes towards exercise recovery supplements.

Questions relating to participant characteristics were included at the start of the survey. In total, the survey featured 32 questions (Appendix B). The survey was administered over a seven-week period during July – August 2020 via *OnlineSurveys* (www.onlinesurveys.ac.uk) and was only available in English. An overview of the methodology can be found in Figure 3.1.

Participants were asked to complete a combination of free-text (open ended) and multiple-choice questions. A vignette was provided within the section "Knowledge of exercise recovery" and "Attitudes toward exercise recovery interventions" to help with contextualization of the following questions. For some multiple-choice questions, participants were prompted to answer further questions, or give a free-text response to provide additional information. For example, if participants answered 'Yes' to the question 'Have you ever purchased an exercise recovery supplement for yourself?' they were directed to answer the follow-up question 'What supplement(s) did you purchase?'.

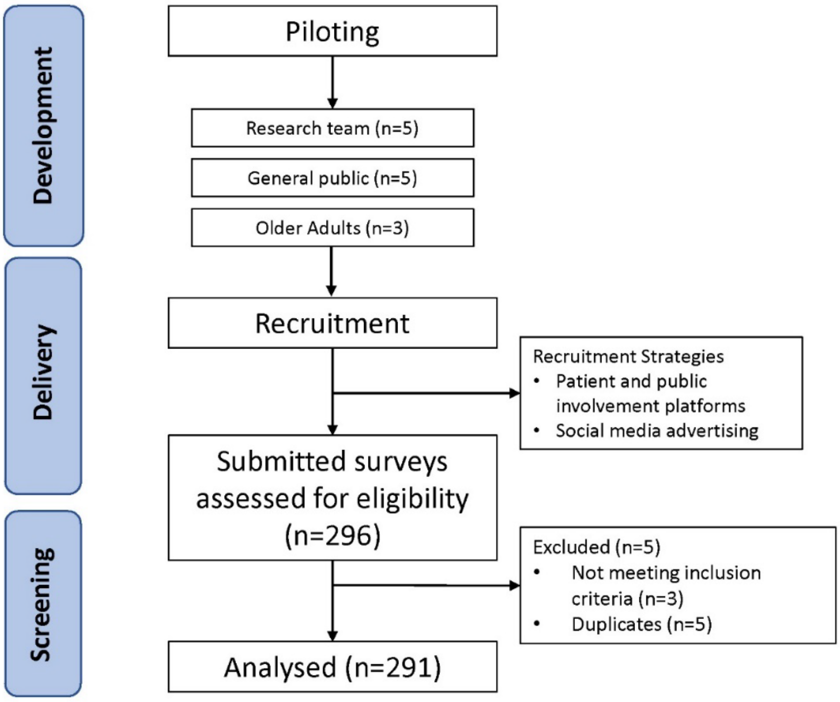

Figure 3.1 An overview of the methodology for the online survey.

3.3.4 Piloting

In the first instance, the survey was sent electronically to all members of the research team to ensure attainment of research aims and some minor amendments to wording and the question order were made. To assess the clarity of the questions and the usability of the survey platform, the survey was piloted by a small sample (5 individuals) of younger adults. Survey responses were also submitted by this group to assess the validity of the questions, alongside ensuring the questions successfully gathered all of the information the researchers required. Finally, the survey was sent to several older adults for further feedback. Only minor amendments were made following this process.

3.3.5 Data analysis

Answers given to multiple choice questions are reported as a fraction followed by a percentage. Conventional content analysis was conducted on responses to open-ended questions through a systematic classification process of coding for the identification of words, themes, or concepts (Hsieh & Shannon, 2005). To achieve this, data were read and re-read to ensure familiarisation and understanding, and interesting aspects or key words within the data were highlighted that captured key concepts in relation to the question. From this, categories and names for the categories were induced. Where more than one code could be derived from a singular free-text answer, codes are reported as a frequency. An example of this is a participant naming more than one recovery strategy within the free-text box. Where codes are mutually exclusive, data are reported as a frequency followed by a percentage. All percentages are rounded to the nearest whole integer.

3.4 Results

3.4.1 Participant Characteristics

At the time of survey closure, 296 responses to the survey had been submitted. After initial screening, five responses were removed (Duplicate participant n=2; Under 70 years of age n=3) leaving 291 older adults (74 $\pm$ 4 years; mean $\pm$ SD) included in the final analysis. Participants were largely independent, with 95 % of respondents requiring no help to perform any activities of daily living, and 89 % reporting at least ‘good’ physical health. Participants were also moderately active. 42 % reported that they regularly participate in aerobic training (e.g., cycling, jogging, spinning classes, dancing, swimming), and 86 % of these people said they participate twice per week or more, with the most popular exercise intensity being ‘moderate’ (68 %). 25 % of individuals reported participating in resistance exercise, and of these 81 % participated twice per week or more. Fewer than 32 % of respondents said that they perform less than one hour of physical activity per day.

3.4.2 Motivators and Barriers to Resistance Exercise

Table 3.1 Motivators for resistance exercise

Code	*n*	Examples
Physical Health	89	
Maintaining/building strength		• Retaining muscle strength which is declining
Weight loss		• If I thought it would help me lose weight
General Fitness		• Wish to keep as fit as possible, enjoy class-based aerobics
Rehabilitation		• Long term recovery from replacement joint surgery
Mobility		• A rapid decline in mobility.
Social benefits	37	
Engaging with others of same age		• Being with like-minded people
Group classes		• To be welcomed into a class
Somebody to go with		• If I had a friend who would participate with me.
Education	19	
Guidance on how to perform exercise		• Need an instructor to show me how to use the equipment.
Advice on safety of exercise		• Assurance that it is safe
Advice on health benefits		• If I was told I needed to do them by a health professional
Accessibility	19	
Local gyms		• Local facilities
Home based		• If I could do it in the home
Age-specific classes		• Accessible gyms with age related classes
Cost	8	
Pay as you go		• Pay as you go. Near to home
Free classes		• Free classes Close to home
Having enough money		• Having enough money to go to gym classes.
Enjoyment	5	
		• I enjoy it. It gives me a buzz.
Psychological benefits	4	
Body image		• Building muscle strength / feeling good about myself
Maintaining mental health		• Desire to maintain physical and mental health
'None'	80	

The most common motivator for engaging in resistance exercise was physical health (31 %) and included 'maintaining and/or building strength', 'weight loss', and 'general fitness' (Table 3.1) Other common themes included social benefits such as 'socialising with others', education, and accessibility. Eighty (27 %) individuals claimed that there were no motivators for resistance exercise. Thirty responses could not be coded either due to a lack of clear information or meaning that might be misconstrued by the researchers, for example, 'gardening', or because there were no other similar responses.

Table 3.2 Barriers to resistance exercise

Code	*n*	Examples
Physical Health	91	
Musculoskeletal		• Arthritis in both wrists and both feet
Cardiovascular		• I have a bad heart
Respiratory		• COPD, Breathing problems
Other		• Numb feet and legs affect balance
Awaiting surgery		• Waiting for my knee replacement(s)
Unspecified		• Health problems
Lack of Motivation	55	
Dislike		• Don't like doing it
No interest		• Not interested in that kind of thing
Laziness		• I hate exercise and am lazy.
Feel no need		• Can't see the need
Accessibility	33	
Covid-19		• Covid-19 at present. Usually I attend Pilates twice a week
Travel		• Having nowhere close to do it
Age suitable		• No age-related gym
No equipment		• Limit equipment available at home
Time	20	
Family commitments		• Time, In a busy day as wife and carer of stroke-survivor husband
Other exercise		• I exercise by walking, housework, gardening, child minding and feel that these constitute enough to keep me healthy and active.
Timing of classes		• Classes are twice a week and I may have something else on those days
General busyness		• Don't really have time, other hobbies pastimes take up most of my time
Cost	9	
Gym Contracts		• Paying in a block. Exercises not suitable long travelling time
Lack of money		• Lack of money and don't want to do on my own as I am very lonely.
Extra expense		• Expense of gym
Lack of Knowledge	9	
Safety practices		• Lack of knowledge as to what might be harmful (I have a displaced vertebra)
Unsure of exercises		• Maybe knowledge/information as to what to do
Unaware of Benefits		• None other than ridiculous for older people.
Social	6	
Lack of social support		• Don't want to do on my own as I am very lonely.
No gym classes		• I need to go to a class, I find it difficult to be motivated alone.
Gym populations		• People who are younger
'None'	52	

The most common barrier to engaging in resistance exercise was physical health (31 %) and included 'musculoskeletal problems', 'cardiovascular health', and 'respiratory problems' (Table 3.2). Other common themes included lack of motivation, lack of accessibility, and time commitments. Fifty-two (18 %) individuals claimed that there were no barriers to resistance exercise. Sixteen responses could not be coded, either due to a lack of clear information or meaning that might be misconstrued by the researchers, for example, 'inertia' or ‘heavy exercise’ or because there were no other similar responses, for example ‘common sense and ‘not enough space in pool’.

Table 3.3 Reasons for recently starting resistance exercise

Code	*n*	Examples
Physical Health	18	• Arthritis of knee. Unable to walk outside without a stick. Needed exercise. Found seated exercises • Just knowing that at my age it is good to keep moving. • Started about 2 years ago following treatment for angina.
Social	4	• Joining friends • Family advice
Enjoyment	1	• I like doing them

Table 3.4 Reasons for recently stopping resistance exercise

Code	*n*	Examples
Health Reasons	15	• Did armchair yoga but stopped due to hip replacement • Lupus and leukaemia
Covid-19	15	• Did do a joint pain management class but Covid lockdown ended that.
Social	6	• Went to the gym to encourage my Husband. He stopped going so did I.
Dislike	5	• got bored with gym
Time	4	• I let other things get in the way.
Cost	3	• Not able to afford the gym fees on my pension

Those that had recently started resistance exercise frequently mentioned physical health (n = 18) as the reason, with some quoting social benefits, and enjoyment (Table 3.3). Those that had recently stopped resistance exercise after previously participating did so most commonly due to health reasons such as surgery (n = 15), or the Covid-19 pandemic (n = 15)(Table 3.4). Other reasons for stopping resistance exercise included withdrawal of social support, a dislike of the gym, cost, and time commitments.

When asked where they would feel most comfortable performing resistance exercise assuming they had been given the appropriate equipment and instructions, home (n = 168) was the most popular choice, followed by the local gym (n = 88), the community centre (n = 58), and outdoor space (n = 35) (Figure 3.2).

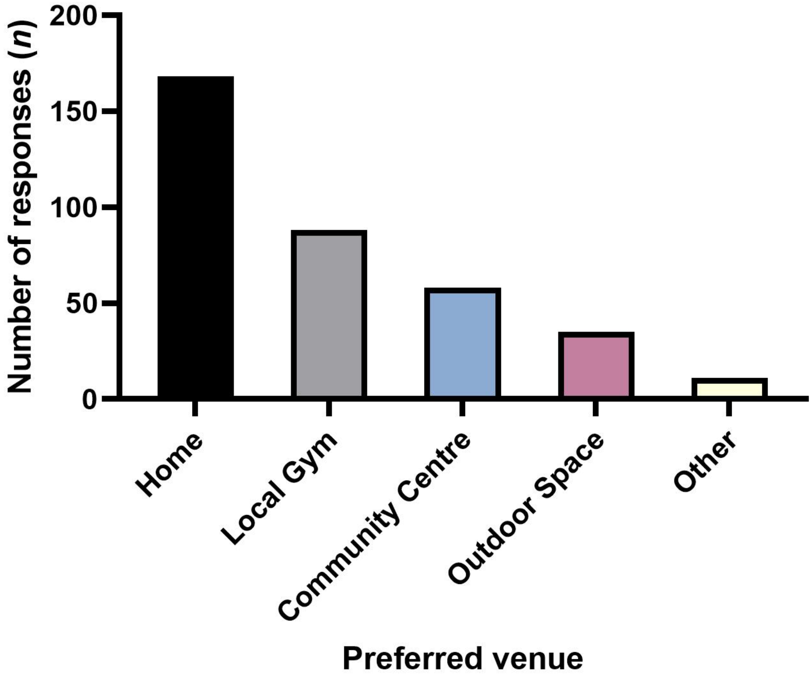

Figure 3.2 Preferred venue for resistance exercise in older adults assuming they are given appropriate equipment and instructions.

3.4.3 Knowledge of Exercise Recovery

Older adults' knowledge of exercise recovery was explored via their understanding of muscle soreness and post-exercise muscle damage. A large majority (93 %) of participants would expect muscle soreness in the days after exercise, but when asked if they had ever heard of delayed onset muscle soreness, or post-exercise muscle damage, only 17 % and 41 % respectively said they had heard of them. When participants that had heard of these terms were questioned further, post-exercise muscle damage was only correctly explained by 6 % of respondents. Delayed onset muscle soreness was generally better understood by those that had heard of it, with 46 % correctly explaining the phenomenon. For both 'post-exercise muscle damage' and 'delayed-onset muscle soreness' a common misconception was that they were a result of performing 'excessive exercise' or 'incorrect exercise technique', or that they were caused by an injury (Table 3.5 and Table 3.6.)

Table 3.5 Coded responses to 'what do you understand by the term 'post-exercise muscle damage'

Code	*n* (%)	Examples
Correct	8 (6.25 %)	• Microscopic changes or tears in muscles • Strains or tears which manifest after the exercise and can be gradual like bruising
Correct with an element of misunderstanding	46 (35.9 %)	
Reference to incorrect exercise technique		• This may happen if you have not exercised in the past and not doing them properly.
Reference to injury		• Means damage or injury to muscles from over exercising or doing it too vigorously
Incorrect	70 (54.7 %)	
Excessive exercise		• I imagine it refers to damage caused by too much exercise; lifting something too heavy, for example
Incorrect exercise technique		• Muscle damage due to not exercising properly
Injury		• Over exercising or doing it the wrong way can cause torn muscles and ligaments, and back problems.
No warm-up or cool down		• Not warming up nor cooling down before and after. Nor gradual work up
Other		• Not breaking down lactic acid • Over tension of muscle groups from holding the muscles tense whilst working then to hard.

Table 3.6 Coded responses to 'what do you understand by the term 'delayed-onset muscle soreness'

Code	*n* (%)	Examples
Correct: 38 (46%)	38 (46 %)	• Muscle soreness especially associated with new strength training. It will go in time. • Soreness often 24-28 hours after extra exercise • A day or so after exercise you would be stiff or sore
Correct with an element of misunderstanding	30 (36 %)	
Reference to excessive exercise		• The muscles responding to excessive exercise after days rather than hours
Reference to injury		• Soreness, joint problems, stiffness even though you have not exercised for some time.
Incorrect time frame		• I think it is something that occurs some days after exercise and takes a long time to get better
Incorrect	15 (18 %)	
Due to excessive/incorrect exercise		• Doing too much too soon and not cooling down properly after exercise • Lifting weights without warm up and weights higher than should be
Other		• In a horse when adrenaline masks symptoms • Build-up of lactic acid in muscles

3.4.4 Attitudes towards Exercise Recovery

When questioned, 52 % of older adults said that muscle soreness may prevent them from completing their daily activities (e.g., gardening, cleaning) at least to some extent, with this number rising to 67 % when asked if muscle soreness would prevent them from completing further exercise (Table 3.7).

Table 3.7 Response to; 'Would muscle soreness prevent you from completing your daily activities/ further exercise until the pain had subsided?'

	Yes (%)	**To Some Extent (%)**	**No (%)**
Daily Activities	10.3	41.9	47.8
Further Exercise	17.5	49.5	33.0

3.4.5 Knowledge of Exercise Recovery Strategies

The most common recovery strategy that older adults' reported using was heat treatment (n = 107), including both hot baths/showers (n = 97) and cold treatments (n = 12). Other common exercise recovery strategies included rest (n = 77), stretching (n = 41), gentle exercise (n = 32), painkillers (n = 31), massage (n = 28), and topical ointments (n = 22) (Table 3.8). The use of nutrition as a recovery strategy was mentioned by only five (<2 %) individuals, of these, only two reported using a high-protein food. Similar themes emerged when asked if they could name any recovery strategies that they had not personally used, with the most frequently mentioned interventions being heat treatments (n = 67) and massage (n = 44)(Table 3.9).

Table 3.8 Strategies used for exercise recovery

Code	n	Examples
Heat Treatment	107	
Hot	97	• Used to take a long soak in a warm bath after a day walking • Hot water bottle
Cold	12	• Use cold compress if necessary • Cold water shower over the muscles
Rest	77	• Have a days rest then exercise muscles again. To get rid of lactic acid. • Rested for a while until it eased
Stretching	41	• Stretched the area if possible • Gentle yoga
Gentle Exercise	32	• Keep going with daily activities but avoid strenuous exercise for a few days and gradually increase. • Took gentle walking exercise. Tried not to sit for long periods.
Painkillers	31	• 2 paracetamol often relieves the soreness and allows me to continue exercising • Take ibuprofen tablets or topical gel.
Massage	28	• Massage the muscles • Used foam roller
Nothing	23	• Nothing, just carried on as normal • Usually gone in a couple of days without any intervention
Topical Ointments	22	• Used over the counter pain relief rubs • 2 x Arnica 30c every 2hrs
Drank Water	16	• Drink plenty of water
Change Exercise Routine	5	• Made sure I didn't push my body all out once start off slowly.
Other	9	• A cup of coffee. • I warmed up before exercise and stretched the muscles afterwards • I know about milk assisting recovery, but usually I don't do anything special.

Table 3.9 Recovery strategies named that they have not previously used

Code	*n*	Examples
Heat Treatment	67	
Hot	53	• Steam bath, sauna, gentle walking • Warm shower after exercise
Cold	27	• Cold water immersion • An ice bath as used by tennis players
Massage	44	• Foam roller-ing. • Maybe massage but I never used this
Gentle Exercise	26	• Gentle exercise, some walking, and stretches. • Possibly a gentle stroll
Topical Ointments	22	• Voltarol or muscular rub • Some people use creams that you rub on
Painkillers	21	• Anti-inflammatory drugs e.g. ibuprofen • Taking pain killers
Stretching	18	• Try to stretch the muscles.
Rest	15	• Wait for recovery to happen • Rest for a few days
Change Exercise Routine	15	• Don't overdo it in the first place. • Don’t do what caused muscle soreness again • Consider other exercise options?
Physiotherapy	7	• Physiotherapist
Milk	3	• More gentle exercise of same affected areas and drinking milk straight after exercise.
Other	23	• Pressure garments • Acupuncture • A sunbed • Use of electrostimulation
‘Don’t know’	70	

3.4.6 Attitudes towards Exercise Recovery Supplements

A large proportion (95 %) of respondents had never bought an exercise recovery supplement. Supplements that they reported buying were protein supplements (n = 3), painkillers (n = 3), sports drinks (n = 2), Arnica (n = 1), Berocca (n = 1), Isostar (n = 1), and anti-inflammatory gel (n = 1). Only seven percent of older adults responded positively when asked their views on exercise recovery supplements, and 49 % expressed negative views such as 'waste of money' (Table 3.10). When asked, 80 % of respondents said that the use of whole foods (e.g., berries, fruit, meat, milk, and fish) was more acceptable than supplements as an exercise recovery strategy for reasons such as 'food is more natural' and it being a 'healthy diet' (Table 3.11). Those that were unsure if whole foods were more acceptable (18 %) generally reported concerns of efficacy (Table 3.12), and those that found whole foods less acceptable (2 %) generally referenced allergies/intolerances or ethical concerns. Despite whole foods being deemed more acceptable than supplements by a large majority of older adults, only 35 % were aware that these foods could aid recovery.

Table 3.10 Views on exercise recovery supplements for older adults

Code	***n* (%)**	**Examples**
Positive	20 (7 %)	• Would be willing to give it a try • Some are beneficial to wellbeing
Neutral	43 (15 %)	• I'd prefer not to take any myself but think it's ok to do so • So so some work, some don't • Proof they worked and how effective their use was to other older people, would be my view.
Negative	144 (49 %)	• I would always be reluctant to take a supplement • Waste of money. • Rubbish-a market encouragement to make money.
No Opinion	84 (29 %)	• I know nothing about them. • No idea, didn't know there was such a thing.

Table 3.11 Reasons for whole foods being more acceptable than supplements

Code	*n*	Examples
Food is more natural	92	• I would rather rely on natural food than supplements • It seems like a more natural process • No artificial additives
It is a healthy diet	47	• Eating those food items would be good for me, regardless of the reason for taking them • Fresh food is essential for good health
Dislike of supplements	24	• I don't like taking supplements or medication if I can avoid them • I am not a great pill popper so doing things through diet makes more sense.
I eat these foods already	19	• They are what I would eat normally anyway. • I have an healthy appetite and love most foods especially fish, so would be more likely to use than say drug relief
Cost/ Accessibility	11	• They carry no additional cost and no profit for charlatans • Easier to implement and probably cheaper
Know what is in food	10	• I prefer to know what I am eating • Don't like not knowing what supplements are made of
Enjoyment of food	9	• More pleasant to consume • I enjoy food
Unassigned	24	

Table 3.12 Reasons for whole foods being as acceptable as supplements

Code	*n*	Examples
Unsure of efficacy	12	• Will it seriously make a difference? • Don't think foods can help • Advertising hype.
Already eat these foods	6	• I try to have a diet including such items already
Open to anything	5	• I'm quite flexible in other views to relieving post exercise pain • Try different things at different times
Food is a better option	5	• Fresh fruit and meat are always a better option • Should eat sensibly all the time
Supplements are easier	3	• Sometimes supplements are easier to take.
Unassigned	11	

3.4.7 Attitudes towards Cow's Milk as an Exercise Recovery Strategy

When asked specifically if they thought milk was an acceptable recovery strategy, 43 % said 'yes' due to already liking milk, or believing in milk's health benefits (Figure 3.3); for example, one participant stated "Milk is a protein and would help building the damaged muscle" (Table 3.13). Those that said milk was not acceptable (27 %) generally disliked milk or had allergies/intolerances (Table 3.15). 31 % said that milk 'may be' be an acceptable recovery strategy, with the most common reasons for hesitancy being that they disliked milk (n = 25), or had not heard of milk as a recovery aid before (n = 20)(Table 3.14). Others that were unsure were also unconvinced of the efficacy of milk for recovery (e.g., "If you could show me the science behind this I would be willing to try"). Just 46 % of respondents said they thought they would be able to drink the suggested 500 mL of milk, and only 44 % said they would be willing to drink 500 mL of milk after exercise.

Table 3.13 Reasons for milk being an acceptable recovery strategy

Code	*n*	Examples
Like milk	44	• I believe that a glass of milk after exercise would be quite refreshing • I like all dairy products and would find it easy to drink more milk
Believe in milk's benefits	40	• Milk is a protein and would help building the damaged muscle • As ex dairy farmer's wife and mother have appreciation of qualities in milk
Drink milk already	17	• I drink quite a lot of milk anyway. • For many years I have consumed full fat, Blue Top milk at home
Natural	13	• Because it is a natural product • I would prefer a healthy drink to drink containing artificial supplements.
Cheap/ Accessible	7	• Milk is readily available • Cheap and easy
Willing to try milk	7	• I don't have a problem with milk, I would try it as a recovery method, and ditch it if it didn't help • I would happily give it a try
Other	7	

Table 3.14 Reasons for milk maybe being an acceptable recovery strategy

Code	*n*	Examples
Dislike of milk	25	• I only drink milk in tea or coffee, or in yogurt form. I don't like it neat much but would drink if I knew it would help. • If it had something else in it not milk alone
Not heard of milk as a recovery aid	20	• I have never heard of milk being recommended • Don't know sufficient about it to give any other answer
Unconvinced of efficacy	11	• If you could show me the science behind this I would be willing to try. • Tried it makes no difference
Drink milk already	7	• I take 200ml of milk as part of my daily intake • Always consumed full fat milk and have tended to eat more cream in old age.
Wary of fat/cholesterol	4	• Don't drink too much as puts weight on. Always drink semi-skimmed
Like milk	3	• I could easily drink more milk. Easiest type of supplement I could use
Medical	2	• I only use milk in tea/coffee and use oat milk otherwise. I have a slight allergy to cow's milk. I have asthma if I drink too much • As type 1 diabetic milk has to be part of carbohydrate intake
Other	19	

Table 3.15 Reasons for milk not being an acceptable recovery strategy

Code	n	Examples
Dislike of milk	47	• Dislike of the taste of milk on its own • I cannot drink milk, as it makes me feel sick, but I do consume it in other ways, e.g. puddings.
Intolerance/ allergy	17	• I am lactose intolerant • My body makes too much calcium so have to be careful how much I take in and I don't like milk by itself
Belief that it is not needed	9	• I already have a good diet and my exercise routine has not suffered for not drinking milk!
Ethical concerns	3	• Cruelty of farming animals
Weight concerns	2	• Extra calories, mucus producing, difficult to transport to outside classes.
Other	2	

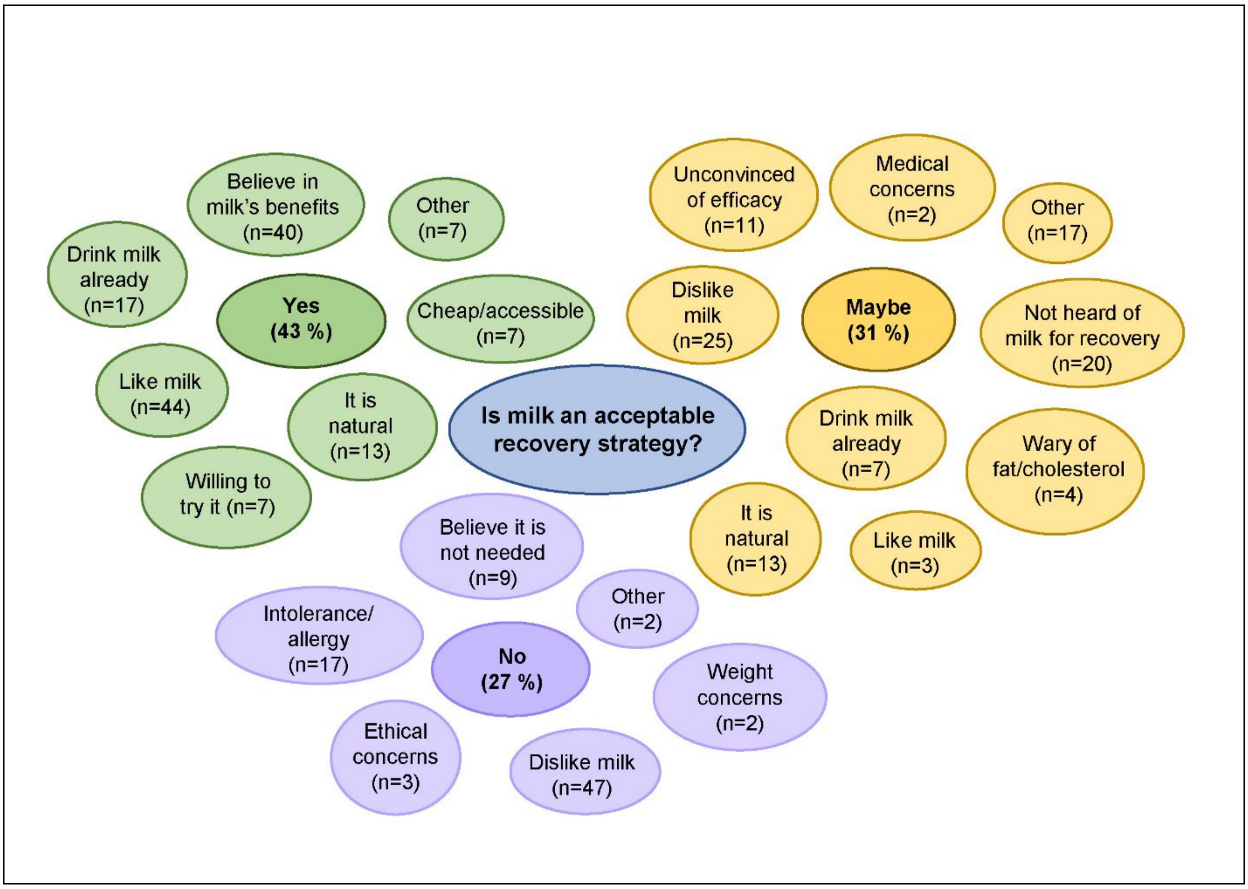

Figure 3.3 Participant responses to 'Is milk an acceptable recovery strategy?' organised by whether milk was deemed acceptable in the previous question (Yes/Maybe/No).

3.5 Discussion

This chapter aimed to understand the perspectives of community-dwelling older adults, and determine their current knowledge of exercise recovery strategies, barriers and motivators to participating in resistance exercise, their preferences for recovery strategies, and their attitudes towards using whole foods, such as milk as a post-exercise recovery aid. To our knowledge this is the first study to explore these concepts in adults over 70 years of age using an online survey platform. The main findings from this study are that knowledge of exercise recovery, and of nutritional strategies for exercise recovery was poor amongst older individuals. Both the greatest motivator and barrier to participating in resistance exercise was physical health, and participants may also be discouraged from completing further exercise if they were experiencing muscle soreness. Due to a largely negative view of supplements for older adults, but despite not being aware of their benefits, whole foods were considered to be more acceptable than supplements for exercise recovery. Cow's milk was also deemed to be an acceptable recovery strategy for older adults, but less than half would be willing to consume the recommended volume after exercise.

3.5.1 Participant Characteristics

Of the 291 individuals that completed the survey, the majority were in good physical and mental health, were largely independent, and were generally physically active, with around a quarter of individuals regularly participating in resistance exercise, a figure that is higher than expected for the general population (Strain et al., 2016). This population is likely not representative of the older population of the UK, and may contain a higher proportion of individuals that maintain interests in exercise and health. It is probable that this self-selection bias has affected the results of the study, to an extent that is unknown. The applicability of the findings of this study to inactive older adults should be considered before recommendations for practice are made.

3.5.2 Motivators and Barriers to Resistance Exercise

Resistance exercise is highly recommended to maintain physical health with advancing age (Dent et al., 2018; Cruz-Jentoft & Sayer, 2019; Hurst et al., 2022), but many older adults do not engage for various reasons (Burton et al., 2017). Understanding an individual's barriers and motivators for resistance exercise could aid in developing interventions to increase uptake and adherence (Michie et al., 2011). In this study, physical health was both the most common motivator and the most common barrier to resistance exercise. Motivators for resistance exercise focused on improving health (e.g. maintaining or building strength, weight loss, and mobility), whereas barriers were often pre-existing medical conditions that the individual perceived as preventing them from participation. This is consistent with other literature in this area, where it is continually reported that physical health is a main motivator for partaking in resistance exercise, but that the perceived health risks of resistance exercise often prevents engagement (Burton et al., 2017; Gluchowski et al., 2022; Cavill & Foster, 2018). These themes were also common in those recently starting, or recently stopping participating in resistance exercise, and in this context was often as a response to a recent health incident. This may be linked to another common theme for motivation – education. A number of individuals stated that education from their clinician pertaining to the benefits of resistance exercise for their health, or their assurance that it was safe, would encourage them to participate. Similarly, a major barrier to resistance exercise was a lack of knowledge and lack of motivation, for example, some participants thought there was 'no need' for this exercise in older adults. This has also been reported in a recent review, where a participant's education, adequate expectations, and knowledge about risks and benefits of exercise was a key factor in determining adherence to an exercise programme (Collado-Mateo et al., 2021a). The COM-B model for behavior change (Michie et al., 2011) suggests that sources of behaviour such as motivation can be influenced by intervention functions such as education and persuasion, which can be implemented on a larger scale through changes to policy. If this model is applied to the current data, it would suggest that educating older adults on the benefits and safety of exercise could increase their reflective motivation to participate in resistance exercise. Additionally, education that provides knowledge of the appropriate physical skills, or knowledge of exercise techniques could also increase perceived capability (another source of behaviour) to perform resistance exercise, and further increase motivation. Clinical advocacy for resistance exercise is therefore likely to be of high importance for encouraging older adults to start, and adhere to, a resistance exercise programme (Collado-Mateo et al., 2021b).

However, even with high motivation to perform resistance exercise, individuals must have access to resources and the opportunity to participate (Michie et al., 2011). The theme of accessibility was present as both a motivator and barrier to resistance exercise, and included issues surrounding a lack of age-suitable gyms, having to travel to local facilities, and a lack of equipment at home. This lack of accessibility may be further compacted by the time constraints of an older population. Many individuals perceived that the time needed to travel to facilities was a barrier, as was the timing of exercise classes alongside their general busyness. There were also financial concerns with the cost of gym memberships. Within the COM-B model, service provision is identified as a policy category that could influence behaviour change. Therefore, improving the provision of exercise classes, or supervised gym sessions for older adults may increase participation to some extent, but it is still unlikely to be feasible for large proportions of the population who do not have the time to travel, or cannot afford to do so. However, when asked, over half of the participants (n= 168) said they would feel most comfortable performing resistance exercise at home. Therefore, a home-based intervention may be the most accessible way to engage and retain older adults in resistance exercise programmes. These programmes have previously been shown to be both feasible, and effective in similar populations (Chaabene et al., 2021; Liu-Ambrose et al., 2019; Hong et al., 2017), and should be a high priority for research and public health initiatives. This desire to exercise at home is somewhat conflicting with the need for social support that was commonly cited as a motivator for resistance exercise. This may be overcome through the use of increased service provision as suggested by the COM-B model. This may include providing online fitness classes which became popular and easily accessible during the Covid-19 pandemic, or through online support groups. For those without access to online platforms, the desire to exercise at could be supported by home visits of exercise practitioners. However, this is likely to be an expensive intervention to implement. It should be acknowledged that the location of the intervention will alter the availability of equipment. For example, it is unlikely that there will be access to fixed-weights machines in a home environment, and hence, work may focus around free-weights or resistance-band exercises, that would provide a different training stimulus (Hurst et al., 2022).

That being said, older people routinely report social barriers to resistance exercise (Hill et al., 2011; Burton et al., 2018), such as having nobody to exercise with, a lack of group classes for older adults, and a lack of social support. This was also true for the current survey, with social factors being one of the most common motivators for resistance exercise, as well as a barrier. For those that seek social interactions from resistance exercise sessions, a home-based intervention may not be as enjoyable. This displays that there is not a one-size fits all approach to encouraging older adults to participate in resistance exercise, and this should be reflected in practice and recommendations.

As a sign of the times, another reason for recently stopping resistance exercise was the Covid-19 pandemic (Chaabene et al., 2021). The temporal timing of this study was such that lockdown restrictions were beginning to lift within the UK, but many major changes to daily life were still evident. Although only mentioned by 15 individuals within our study, it should be obvious that the pandemic has changed many older adults' willingness and ability to engage in resistance exercise programmes both inside and outside of their homes. Research aiming to engage older adults in such exercise after the pandemic may find differing results to that conducted before March 2020, and data on how motivators and barriers to resistance exercise have changed would be welcomed by the literature.

3.5.3 Knowledge of Exercise Recovery

In general, older adult's knowledge of the exercise recovery process was poor. Although the majority of respondents said that they would expect muscle soreness in the days following intense exercise, only 17 % said they were familiar with the term 'delayed onset muscle soreness' and less than half of these correctly described the phenomenon. A common misconception amongst these individuals was that muscle soreness was a result of excessive exercise or by exercising incorrectly. For example, one participant described delayed onset muscle soreness as 'Doing too much too soon and not cooling down properly after exercise'. These misconceptions may lead people to believe that if they are experiencing muscle soreness that they had done something 'wrong' in the previous exercise session or they were at risk of becoming injured, and this may affect their confidence to continue with resistance exercise. Similar results were found when it was asked what individuals understood by the term 'post-exercise muscle damage'.

The actual implications of a lack of knowledge of exercise recovery in older adults is unknown, and we are unaware of any corresponding literature in younger populations. However, logically, it follows that for older adults who are unfamiliar with resistance exercise, educating them on topics surrounding exercise recovery, as recommended to increase motivation by the COM-B model, may reduce attrition from exercise programmes. Specifically, guidelines should suggest that clinicians and practitioners should inform individuals that some muscle soreness is a normal component of the adaptation process and is to be expected following intense exercise (Hurst et al., 2022; Michie et al., 2011).

3.5.4 Attitudes towards Exercise Recovery

An important finding of the current study, and one that supports the need for clinical advocacy of muscle soreness being expected, as discussed above, is that older adults believe muscle soreness would affect their physical activity levels until the pain had subsided. Indeed, over half (52 %) of the older adults surveyed said that they would be discouraged from completing their usual daily activities if they were experiencing DOMS. This figure increases to 67 % when older adults were asked if they would be discouraged from completing further exercise. Literature investigating the link between DOMS and non-exercise physical activity is lacking. However, these results may be tenuously linked to several studies aiming to explore the effect of structured exercise programmes on non-exercise physical activity, but data are conflicting (Silva et al., 2018; Fedewa et al., 2017). It has been suggested that the initiation of an exercise programme may prompt individuals to acutely decrease their non-exercise physical activity (Van Etten et al., 1997), although this may be affected by session duration (Fedewa et al., 2017), intervention length (Fedewa et al., 2017), activity type (Drenowatz et al., 2015), and age (Goran & Poehlman, 1992; Meijer et al., 1999). Of more relevance to the current study, it has recently been shown that greater morning fatigue is associated with a lower volume and intensity of non-exercise physical activity during a power and resistance exercise programme (Vetrovsky et al., 2021). Specifically, one point greater on the fatigue scale was associated with 3.2 minutes less of moderate-vigorous physical activity that day. These findings begin to illustrate how physical activity levels, and possibly activities of daily living (ADLs), may be affected in the acute period after exercise in older adults (Vetrovsky et al., 2021). However, we concede that these previous studies do not directly measure, or attempt to correlate muscle soreness with decreased physical activity, but we are unaware of any such studies that do so. It should also be noted that these studies are often not designed to detect short-term within-subject changes in non-exercise physical activity and hence may be less useful when investigating the exercise recovery process. Therefore, our finding that older adults believe they would decrease physical activity levels as a result of muscle soreness represents an interesting new avenue for this area of research. Should data support our findings, this may have important implications for the prescription of muscle damaging exercise in older adults and represents a need to identify suitable exercise recovery strategies for this population.

3.5.5 Knowledge of Exercise Recovery Strategies

To determine what older adults currently know about exercise recovery strategies, participants were asked what exercise recovery strategies they had used in the past. The most common recovery strategy was the use of heat treatment by approximately a third of older adults, which included both hot (e.g. using a hot water bottle)(n = 97) and cold (e.g. using a cold compress)(n = 12) treatments. As the use of heat treatments is widely used for muscular complaints and injuries, this is perhaps unsurprising. Interestingly, rest was only the second most commonly stated recovery strategy, but this could be due to rest being a passive strategy, rather than being thought of as an active recovery strategy. Gentle exercise, stretching, massage, and topical ointments such as heat rub, were also popular. Drinking water was mentioned on 16 occasions as a recovery strategy. However, other than drinking water, nutrition was mentioned by only five individuals. Considering the research to date demonstrating the potential effectiveness of nutrition as a recovery aid for both younger (Sousa et al., 2014; Heaton et al., 2017; Davies et al., 2018) and older adults (Clifford, 2019), it is surprising that few older adults in this survey reported nutrition as a strategy to help muscle soreness. This suggests a discord between the knowledge of researchers and older members of the general public population, and displays a need for improved education and patient and public involvement when identifying suitable exercise recovery strategies for older adults (Michie et al., 2011).

Similarly, protein as an exercise recovery aid was mentioned by only two individuals (<1 % of the sample). The low reported incidence of dietary protein as a recovery aid in the current study may have been exaggerated as a result of a general lack of understanding of exercise recovery and muscle soreness as a whole. However, our findings may demonstrate a lack of awareness, or understanding, of the benefits of dietary protein amongst older adults. Although not directly investigating protein for exercise recovery, a recent study has also found poor knowledge of dietary protein amongst 1825 community-dwelling European older adults. Using an online survey, it was determined that 35.3 % of the sample did not know what dietary protein was, and low protein knowledge was observed in 902 (49.4 %) participants of the total study sample (Visser et al., 2021). Of more relevance to the current study is that amongst individuals with low protein knowledge, only 65 % responded correctly to the statement that "You need protein in the diet for repairing bones and muscles". Similarly, a recent feasibility study has shown that giving older adults dietary advice and protein rich food products increased their dietary protein intake over four weeks, and most reported that they would continue following the advice on cessation of the study (Reinders et al., 2020). If these results are translatable to a post-exercise setting, it is possible that there would be good compliance with protein-rich foods as an exercise recovery strategy. As a whole, these findings demonstrate a clear need to educate older adults on the benefits of protein if we are to encourage them to alter their dietary habits, both for health and as an exercise recovery strategy (Michie et al., 2011). However, this is not necessarily exclusive to dietary protein. As mentioned previously, very few individuals named nutrition as an exercise recovery strategy and hence, education of several areas of nutrition may be warranted for older adults.

3.5.6 Attitudes towards Exercise Recovery Supplements

Exercise recovery supplements have been shown to be efficacious (Harty et al., 2019) and are widely used (Garthe & Maughan, 2018; Jovanov et al., 2019) in younger adults.

However, the vast majority of older adults in this study had never bought an exercise recovery supplement, and less than 1 % had ever bought a protein supplement. Given the previous finding that older adults' knowledge of dietary protein for exercise recovery is limited, it is perhaps unsurprising that so few had purchased exercise recovery supplements. Older adults' views on exercise recovery supplements is likely also a factor in how few had purchased a supplement in the past. Indeed, only 7 % of older adults in this sample expressed a positive opinion of exercise recovery supplements, and almost half voiced a negative opinion (e.g. "*Rubbish - A market encouragement to make money*"). It is therefore unlikely that there would be good compliance to any recommended exercise recovery supplement for older adults. Instead, research may wish to focus on the use of commonplace foods that older adults are familiar with, and can access easily at their supermarket or food supplier.

In support of this, the current study found evidence that whole foods (e.g., berries, fruit, meat, milk, and fish) were a more acceptable recovery strategy than supplements by a large majority (80 %) of older adults, despite over a third of older adults not being aware that these foods could aid recovery. The most common reason for this is that food was considered more natural or healthy. However, another common reason for finding whole foods more acceptable was simply a strong dislike of supplements. As mentioned by a number of participants, a whole food approach is also often cheaper than supplements, and hence could be more accessible to a greater proportion of older adults.

Emerging literature also suggests that a food-first approach could be more effective in enhancing post-exercise muscle remodelling when compared with isolated protein supplements in younger adults (Burd et al., 2019). This is because whole foods often contain other non-protein nutritive components (e.g. carbohydrates, lipids, micronutrients) that may interact to increase muscle protein synthesis rates beyond those expected from isolated proteins alone (Burd et al., 2019). Interestingly, such foods that may be useful for exercise recovery in older adults (e.g., meats, fish, eggs, legumes, nuts, and dairy) have also been shown to be myoprotective (Granic, Dismore, et al., 2020; Granic, Hurst, Dismore, Aspray, Stevenson, Miles D Witham, et al., 2020), and so their increased consumption would likely complement resistance exercise to further preserve muscle mass and strength. Therefore, future research aiming to identify exercise recovery strategies for older adults could focus on a food-based approach to ensure uptake and adherence, whilst also considering the overall effectiveness of the food-stuff in a post-exercise setting.

3.5.7 Attitudes towards Cow's Milk as an Exercise Recovery Strategy

The high-protein content of milk (3.6 g/100 mL) alongside its nutritional composition of carbohydrates, fats, and micronutrients suggests it could be useful for aiding exercise recovery (James, Stevenson, Rumbold., et al., 2019). Indeed, milk has previously been shown to be an effective exercise recovery strategy in younger adults (Rankin et al., 2015; Cockburn et al., 2008, 2012), and has been shown to be beneficial for skeletal muscle health (Granic, Hurst, Dismore, Aspray, Stevenson, Miles D Witham, et al., 2020), but it's acceptability to older adults is uncertain (Dismore et al., 2020; Granic, Hurst, Dismore, Stevenson, et al., 2020). We explored older adult's attitudes towards milk as a high-protein exercise recovery strategy. In our survey, nearly half of older adults considered milk to be an acceptable recovery strategy, whilst approximately a quarter of older adults thought milk was unacceptable, and gave reasons such as dislike of milk, allergies, intolerances, and ethical concerns. Those that thought milk might be acceptable either disliked milk by itself, or had not heard of the benefits of milk as a post-exercise recovery strategy. This suggests that milk may be more acceptable to a larger proportion of older adults if they were educated on the benefits of milk, but there is currently no evidence to support this.

We have identified one recent study which explored older adults' attitudes and barriers to engaging in a resistance training program and consuming a recovery drink (bovine milk) after exercise (Dismore et al., 2020; Granic, Hurst, Dismore, Stevenson, et al., 2020). The study conducted semi-structured interviews after a six-week exercise and nutrition intervention aiming to understand older adults' barriers and motivations for engagement. The study concluded that older adults considered milk to be an acceptable post-exercise recovery drink. Only one participant struggled with the volume of milk (2 x 500 mL), but overall both the taste and volume of liquid were viewed as acceptable. Of interest is that some participants did not think they would find milk acceptable before the intervention, but began to look forward to consuming their drink (Dismore et al., 2020). The authors concede that there is currently no evidence examining the efficacy of cow's milk for post-exercise recovery in older adults. However, data from the pilot study of community-dwelling older adults suggests that cow's milk is both an acceptable and feasible post-exercise intervention for this group (Granic, Hurst, Dismore, Stevenson, et al., 2020). Granic et al. (2020) reported the compliance to consuming 2 x 500 mL of milk after resistance exercise twice per week for six weeks of 97.1 % and 98.3 % for whole milk and skimmed milk, respectively in the group of 29 older adults.

Additionally, no participants reported finding the milk intervention difficult, or saw the volume of milk as a barrier. Only two participants reported minor changes to their usual diet as a result of the milk intervention (Granic, Hurst, Dismore, Stevenson, et al., 2020). This suggests that should milk be found to be beneficial in older adults, it would be a suitable and accepted strategy for post-exercise recovery. It should be recognised that this study had a small sample size, and participation was likely dependent on the individuals having a positive predisposition towards milk consumption, and hence, the acceptability of this intervention amongst the general population is still unclear. This is promising for milk as an exercise recovery strategy for older adults, but further research must first be conducted to determine the efficacy of milk for recovery in an older population, and to explore other potential high-protein recovery strategies that may be more acceptable.

3.5.8 Strengths and Limitations

This is the first study that has attempted to understand older adults' knowledge of, and attitudes towards, exercise recovery and exercise recovery strategies. The results of this study are mapped to the COM-B model of behaviour change to make recommendations for effectively implementing resistance exercise programmes in older adults, and will direct future research to identify effective and acceptable exercise recovery strategies for older adults. The use of an online platform to gather these data allowed a high number of participants to be recruited from across the United Kingdom. However, some groups, likely those of lower socio-economic status, minority ethnic groups, or the very old, may not have been represented due to a lack of internet access. A self-selection bias is likely also present, and would preferentially recruit those that are interested in topics of health and exercise in older adults. The literature would benefit from a similar study that uses semi-structured interviews to address our aims, as this will allow researchers to probe for further information, which was not possible with our survey. Interviews conducted within the community may also allow access to individuals whose views have not been captured by the current study.

3.6 Conclusions

In summary, older adult's knowledge of exercise recovery was limited, and there is a clear need for education, especially concerning the process of exercise recovery, and the role of nutrition for aiding exercise recovery. Physical health was the most common motivator and barrier to resistance exercise, and uptake of resistance exercise by older adults may be improved through education, or home-based exercise interventions. Older adults were much more accepting of whole foods as a recovery strategy than supplements although knowledge of their benefits is poor. This may be because supplements were largely viewed negatively by the respondents. Whilst whole foods represented an acceptable exercise recovery intervention for community-dwelling older adults, the majority were unaware of the potential benefits of nutrition for post-exercise recovery. Older adults may benefit from education about beneficial interventions such as nutrition for exercise recovery, and further research should be conducted to determine the efficacy of a range of whole foods for improving exercise recovery.

Chapter 4 : Bovine Milk – a Nutritional Intervention for Acute Exercise Recovery in Older Adults?

4.1 Abstract

Aim

To examine the effectiveness of whole bovine milk for ameliorating markers of EIMD and expediting exercise recovery in older adults following resistance exercise versus skimmed milk and a control drink. Also, to assess the applicability of any findings to a real-world setting by gathering further data regarding older adult's views on exercise recovery, exercise recovery supplements, and using milk as an exercise recovery supplement via an exit survey of study participants.

Methods

In a single-blind, placebo-controlled, parallel groups design, ten older adults (75.6 ± 4.6 y) were randomized to one of three experimental treatment arms; skimmed milk, whole milk, or fruit juice. After performing resistance exercise (four sets of ten repetitions at 70 % 1-RM of three lower limb exercises; leg press, knee extensions, and hamstring curls) participants consumed 2 x 500 mL of their assigned drink. Measures of EIMD and exercise recovery recorded at 0-, 24-, 48-, and 72-hours after exercise were compared with pre-exercise values. Participants completed an exit survey after the last visit, gathering data on their experiences of the study.

Results

Recruitment for this study was difficult, and it is therefore not sufficiently powered. No effect of the resistance exercise protocol could be determined on MIVC, perceived recovery, postural stability or time to complete five chair stands. No significant differences were observed between groups at any time point in any marker of EIMD. All drinks were received positively, but there were some concerns regarding volume.

Conclusions

This chapter could not determine the effectiveness of milk as an exercise recovery aid in older adults. However, it does provide recommendations for progressing research surrounding exercise recovery in older adults by discussing various methodological and applicability considerations. Milk could be an acceptable recovery strategy in older adults, but other whole foods may be preferred.

4.2 Introduction

As highlighted in Chapter 1, maximising the potential benefit of resistance exercise programs by ensuring optimal recovery is an important aim. Indeed, any transient decrements in physical functioning as a result of resistance exercise could be detrimental to an older individual when performing habitual daily activities (Moore et al., 2005; Papa et al., 2015). Therefore, many studies are now seeking to identify interventions to expedite exercise recovery in ageing athletes (Clifford, 2019). However, as discussed within Chapter 2, there is currently only one study that has previously aimed to assess the effectiveness of a recovery strategy in older (65+ years) adults (Naderi et al., 2021), and none that use nutrition as a recovery aid.

A nutrition-based recovery strategy that has recently acquired considerable interest is the consumption of protein, and more recently, the consumption of protein-rich whole foods. One intervention that is naturally high in proteins that has been explored in recent literature is the use of bovine milk. Milk has gained popularity as a post-exercise supplement in younger adults due to its abundance of high quality proteins, vitamins, minerals, carbohydrates, and fats (Granic, Hurst, Dismore, Aspray, Stevenson, Miles D Witham, et al., 2020). Specifically, the combination of proteins found in milk, including whey protein, known to rapidly stimulate muscle protein synthesis, and casein, which digests slowly to maintain muscle protein synthesis for several hours after ingestion, could be beneficial for exercise recovery (Granic, Hurst, Dismore, Aspray, Stevenson, Miles D Witham, et al., 2020; West et al., 2017). Indeed, ingestion of milk one-hour following exercise has been shown to result in a more positive net protein balance, possibly due to both an increase in muscle protein synthesis, and a decrease in muscle protein breakdown (Elliot et al., 2006). Several studies have already found milk an effective means for improving acute recovery after exercise in younger adults (Alcantara et al., 2019). For example, 500 mL of semi-skimmed milk was found to reduce decrements in peak torque, creatine kinase, and myoglobin 48-hours after muscle damaging exercise when compared with low-fat chocolate milk, a carbohydrate beverage, and water in young males (21 ± 3 years) (Cockburn et al., 2008). Similar results have been found in a study employing both male and female athletes (Rankin et al., 2015). The potential for milk to ameliorate EIMD is therefore clear.

However, for a nutritional intervention to be effective, it must be regularly consumed, and hence it must also be acceptable to the population for which it is recommended. For older adults, this also means it must be affordable and easily obtainable. As milk is readily available and inexpensive, it could be an ideal supplement for acute recovery nutrition in older adults. Milk has already been shown to be an acceptable intervention to older adults following a resistance training session (Granic et al., 2019; Dismore et al., 2020), and further evidence for its acceptability can be found in Chapter 3 of this thesis, where it was found that up to half of older adults would consider milk to be an acceptable recovery strategy.. Additionally, it seems consuming dairy beverages post-exercise may not affect energy intake for the rest of the day (Brown et al., 2016), and would therefore increase older adults daily protein and energy intake as opposed to replacing meals that may usually be eaten throughout the day. This is a particularly important consideration when choosing protein supplements for the older population due to their already often diminished appetite and poor energy intake.

Interestingly, there is some evidence to suggest that the fat content of milk may affect net muscle protein synthesis after exercise (Elliot et al., 2006). A series of studies in resting younger adults initially found that the addition of fat and sucrose to milk proteins resulted in greater nitrogen retention in the post-prandial hours, and it was postulated that this may be due to fat delaying gastric emptying and dietary amino acid absorption (Fouillet et al., 2001). Following this, Elliot and colleagues (2006) found that phenylalanine and threonine uptake in both legs, which in this study was thought representative of net muscle protein synthesis, was found to be highest after ingesting whole milk, compared with fat-free milk and isocaloric fat-free milk over 4-hours post-exercise (Elliot et al., 2006). Although both groups consuming fat-free milk did also experience an increase in amino acid uptake, it should be noted that even when matched for calories, whole milk provided a greater anabolic stimulus. The findings would suggest that whole milk has a greater potential to aid exercise recovery compared with skimmed milk, due to the higher fat content. However, these data were collected in young adults, and the theory that whole milk may lend additional benefits to exercise recovery is currently lacking strong evidence, especially in an older population. Based on the literature, we propose that it would be beneficial to both establish if milk can enhance recovery in older adults, and if any such effect is enhanced when whole milk is consumed compared with skimmed milk.

Throughout this thesis, it has been highlighted that there is currently little understanding of how older adults experience exercise-induced muscle damage, both physiologically and from the individual’s viewpoint. For example, Chapter 2 illustrates that there is little knowledge surrounding an older adult’s acute response to a ‘typical’ resistance exercise session, and especially few studies reporting on markers of exercise-induced muscle damage that may be deemed more relevant to an older adult, such as Timed Up-and-Go tests or postural stability measures. Indeed, most of the pre-existing studies use maximal voluntary contractions as a primary means to assess physical functioning. Therefore, the study presented within this chapter has been designed to be applicable to a 'real-world' scenario, both to contribute data to the characterisation of exercise-induced muscle damage within this population, but also to ensure any positive effects of milk for exercise recovery are meaningful to older adults performing usual resistance exercise sessions.

Accordingly, the aims of this study were two-fold. Firstly, given the current evidence for the benefits of milk for exercise recovery in younger adults, and the potential for fats to aid recovery, we examined the effectiveness of whole bovine milk for expediting exercise recovery, or attenuating muscle damage in older adults following resistance exercise, versus skimmed milk and a carbohydrate control drink. The primary outcome was maximal isometric voluntary contraction (MIVC). Secondary outcomes were perceived muscle soreness, perceived recovery, postural stability, timed up-and-go and time to five chair stands. Secondly, to assess the applicability of any findings to a real-world setting, the study aimed to use an ecologically valid resistance exercise session to induce muscle damage, and gather further data regarding older adult's views on exercise recovery, exercise recovery supplements, and using milk as an exercise recovery supplement via an exit survey.

4.3 Methods

4.3.1 Ethical Approval

This study was granted ethical approval by the Faculty of Medical Sciences Research Ethics Committee of Newcastle University. The study was conducted in accordance with the declaration of Helsinki. All participants provided written informed consent prior to participation alongside a research team member trained in Good Clinical Practice.

4.3.2 Participants

All participants within this study were recruited from the North East of England, United Kingdom from March – September 2022. The primary method for recruitment was via VOICE®, a public involvement platform for members of the community that are interested in being involved with health research. In an attempt to reach a larger audience, the study was also advertised via a staff bulletin, Facebook®, Twitter®, and posters were displayed at various locations in Newcastle upon Tyne including local churches and libraries. Other community groups were emailed with information and posters and were asked to circulate these to their members. All individuals that were interested were emailed or posted a participant information pack detailing the study requirements and procedures before deciding if they wished to participate.

Prospective participants were screened against relevant inclusion/exclusion criteria. Participants were required to be over 70 years of age, willing and able to drink bovine milk, and report that they did not currently, or have not within the last year, performed any resistance exercise. During a screening visit, a full verbal explanation of the study was given, and the opportunity was given to ask any questions that arose. Participation was dependent on the successful completion of the Physical Activity Readiness Questionnaire (PAR-Q+) 2020, and a long-term health history questionnaire confirming that there were no medical contraindications to exercise during this visit. A Rapid Assessment of Physical Activity (RAPA) was also completed to determine the physical activity status of participants. Using prior data collected from Rankin et al (2018)(Rankin et al., 2018) detailing changes in peak torque of the knee flexors at 60°/s between baseline and 24-hours for a milk versus carbohydrate drink a power analysis using G*power (version 3.1.9.2) with ANOVA repeated measures, within and between interactions (groups = 3, assessment times = 5, and correlation among repeated measures = 0.5) was performed to determine appropriate sample sizes. With an effect size of 0.22, a 2-tailed significance level (α) of 0.05, and the desired power ($1-\beta$) of 0.80, a sample size of 36 with 12 participants in each group was needed.

4.3.3 Experimental Design

In a single-blind, placebo-controlled, parallel groups design, participants were randomized to one of three experimental treatment arms; skimmed milk, whole milk, or isocaloric red grape juice. The participants were randomly stratified using sex and maximal isometric voluntary contraction (MIVC) scores as blocking factors. These scores were collected from the screening and familiarisation visit conducted >2 weeks before experimental testing. For researcher blinding purposes, the three experimental arms were referred to as A, B, and C throughout the course of the experiment. Supplements were prepared and distributed to participants by laboratory technicians that were not involved with data collection. Participants could not be blinded to their condition. The research team were un-blinded to the conditions after data collection and analysis.

Participants reported to the Newcastle University Sports Science laboratories on five occasions. Prior to the main experimental visit, participants attended the laboratory for health screening, familiarisation of function tests and determination of one-repetition maximum (1-RM) values. Experimental testing was then conducted over four consecutive visits and therefore measured recovery up to 72-hours post-exercise. Participants reported to the laboratory at the same time each day (± 1 hour). On arrival to the first experimental visit, baseline measures of MIVC, perceived recovery, muscle soreness, and physical functioning were conducted. The participant then performed the resistance exercise protocol. Further measures of maximal isometric strength, perceived recovery, muscle soreness, and physical functioning were repeated at immediately after, and 24-, 48-, and 72-hours after the resistance exercise protocol (Figure 4.1).

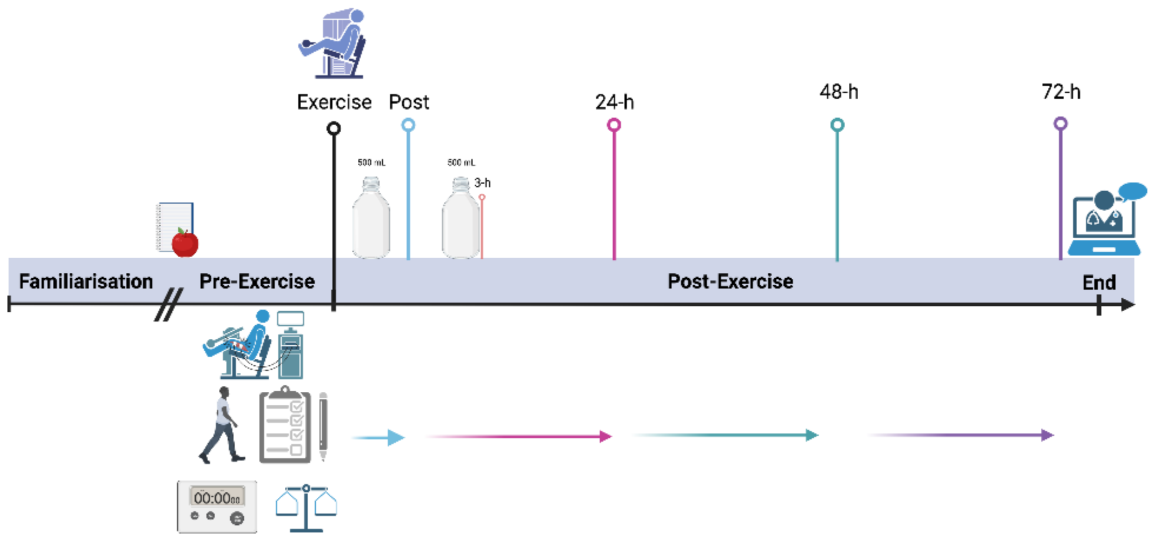

Figure 4.1 Protocol Schematic

4.3.4 Pre-Laboratory Stipulations

Participants were asked to avoid bouts of strenuous activity 24-hours prior to the first experimental visit, and for the remainder of the trial (96-hours in total). Participants were also instructed to avoid consuming any nutritional supplement (e.g., whey protein, vitamins, creatine), or receive any alternative treatments (e.g., massage, cold water immersion, hot baths etc.) for the duration of the study. A food diary was recorded for the 24-hours prior to the first experimental visit for analysis and comparison between groups.

4.3.5 Dietary Intervention

Nutritional information of the given experimental and control drinks can be found in Table 4.1. Immediately after performing the resistance exercise protocol, participants consumed a 500 mL bolus intake of either (1) Whole milk (Arla Cravendale®, Arla Foods Ltd., Leeds, UK), (2) Skimmed milk (Arla Cravendale®, Arla Foods Ltd., Leeds, UK), (3) isocaloric control drink (Sainsbury's, London, UK). The isocaloric control drink was red grape juice and was chosen to match whole milk energy content. An additional 500 mL of each supplement was consumed within three hours of leaving the laboratory. Participant's compliance with the consumption of their supplements was confirmed during their next visit to the laboratory. This volume (500 mL) was given as it provides the roughly ~20 g of protein needed to stimulate muscle protein synthesis above that provided by resistance exercise (Witard et al., 2014; Pennings et al., 2011), and is routinely used in similar studies in younger (Rankin et al., 2015; Cockburn et al., 2012) and older (Granic, Hurst, Dismore, Stevenson, et al., 2020) adults. 1 L packs of all supplements were purchased to coincide with experimental visits and were stored in a refrigerator within the Sports Centre at Newcastle University. Compliance was assessed by asking for verbal confirmation at their next study visit that they had consumed all of the supplement within the required time.

Table 4.1 Nutritional composition of drinks

	Whole Milk (per 500 mL)	Skimmed Milk (per 500 mL)	Red Grape Juice (per 500 mL)
Energy (kcal)	325	185	320
Fat (g)	18	1.5	2.5
Carbohydrate (g)	23.5	24.5	114.5
Sugars (g)	23.5	24.5	105
Protein (g)	17	18	2.5
Salt (g)	0.05	0.5	0.4
Vitamin B12 (µg)	1.5	1.5	0
Potassium (mg)	810	840	955
Calcium (mg)	610	645	70
Iodine (µg)	160	155	0
Vitamin B6 (mg)	0	0	0.5
Vitamin C (mg)	7.5	0	20

4.3.6 Resistance Exercise Protocol

Participants were given the opportunity to warm-up for 5-mins on a cycle ergometer (Wattbike, Nottingham, UK) before beginning the resistance exercise session. In an attempt to replicate what would be considered a common resistance exercise session to ensure ecological validity, the participants performed four sets of ten repetitions at 70% 1-RM of three lower limb exercises; leg press, knee extensions, and hamstring curls. These were performed on fixed weights machines (Attack Fitness, Stoke-on-Trent, UK/ XS Sports, Shrewsbury, UK), with two minutes rest between each set. Participants were instructed to perform the eccentric components of the lift in a controlled manner. This is similar to the exercise protocol used by Naderi et al. (Naderi et al., 2021), but used larger muscle groups of the lower limbs, and was altered after pilot testing to reflect what researchers thought was attainable using our specific equipment. After each exercise, participants were asked their rating of perceived exertion (RPE) using the Borg scale (GA Borg, 1998; G Borg, 1998), where 6 was anchored ‘no exertion at all’ and 20 meant ‘maximal exertion’.

4.3.7 Estimating 1-RM

Using Brzycki's (1993) theory for predicting a 1-RM from repetitions to fatigue (Brzycki, 1993), 1-RM for each participant, on each of the exercises, was estimated from strength testing during the screening visit. This has been shown to be valid for use in older adults (Wood et al., 2002). This protocol was followed due to the potential risks, and practical implications that arise from older adults attempting a 1-RM lift. This protocol instead uses sub-maximal efforts to estimate maximal strength, thought to be more suitable for an older population. To estimate 1-RM from submaximal loads, Brzycki uses literature by Sale and McDougal (1981)(Sale & MacDougall, 1981) who noted that assuming there is a direct relationship between repetitions to fatigue and the percentage of maximal load lifted, the amount of repetitions that can be performed should decrease in a linear fashion as weight increases. However, this relationship is not linear beyond ten repetitions, and hence, the equation Brzycki proposes for estimating 1-RM is not applicable if the individual can perform more than ten repetitions. Brzycki's proposed equation is as follows:

Predicted 1-RM = Weight lifted/(1.0278 - 0.0278X)

*where X = the number of repetitions performed

Starting with leg press, followed by hamstring curls, and then knee extensions, the researcher used previously collected MIVC values to estimate an initial weight for the participant to attempt. Participants were instructed to attempt to lift the given weight for as many repetitions as they could manage, up to ten repetitions. If ten repetitions could be completed, the weight was increased following a rest interval. The magnitude of weight increase was dependent on participants rating of difficulty, and the researcher's assessment of effort. When a participant could not complete ten repetitions of a weight, the weight and repetitions achieved for that set were recorded and Brzycki's equation was used to estimate 1-RM. Generally, participants performed two to four sets before fatigue.

4.3.8 Data Collection

Anthropometry

On completion of the screening forms, participants had their body mass (0.1kg) (Seca Ltd, Germany) and stature measured to the nearest 0.1 cm (Stadiometer, Seca Ltd) wearing only light clothing and no footwear.

Maximal Isometric Voluntary Contraction

Maximal Isometric Voluntary Contraction (MIVC) was collected during familiarisation as a blocking factor for supplement allocation, and during all experimental visits. MIVC was collected to ensure comparability of our data to previously published studies that were discussed in Chapter 2. MIVC of the knee extensors was measured with a Biodex Isokinetic Dynamometer System 4 Pro™ (Biodex Medical Systems Inc, New York, USA) and Advantage BX Software 5.3X (Biodex Medical Systems Inc, New York, USA). Participants were seated upright, with the attachment arm strapped to the distal part of the lower leg, just above the ankle joint, and at a knee flexion of 90°. To prevent any abduction, adduction, or flexion of the hip, the distal part of the thigh was strapped to the chair, and further straps were applied to the waist and torso. Participants were positioned so that the patellofemoral joint was aligned with the pivot point of the attachment arm. Once the researcher was happy with the position of the participant, the precise configuration of the dynamometer was recorded to be replicated during each visit. During data collection, participants were asked to place their arms over their chest, rather than gripping the available handles, to further isolate the knee extensors.

Participants performed four unilateral maximal contractions, separated by 30 seconds of rest. After a three-second countdown, participants were instructed to maximally extend their knee flexor after hearing the command 'push' and hold the contraction for five seconds. The position of the limb did not change during contraction and remained at 90°. Participants received no verbal encouragement during contraction, only a countdown of the five seconds. During the screening visit, participants performed this protocol on both of their legs to determine a dominant side. During all experimental testing, MIVC was measured using the dominant leg only, defined as the leg that achieved the highest peak torque.

Perceived Muscle Soreness

Participants rated their passive perceived muscle soreness using a 100 mm visual analogue scale with 0 meaning 'no pain' and 100 indicating 'extreme pain'. Pain was indicated by drawing a vertical line on the scale. Line placement was then measured with a ruler from 0, and recorded in mm.

Perceived Recovery Scales

In order to ensure adherence to exercise programs we must consider when older adults might feel ready to perform a subsequent exercise session. Using the same methodology as that described by Borges et al. (2018) we obtained perceptual measures of motivation, fatigue, and total recovery using Likert scales.

To monitor perceptual responses to resistance exercise and subsequent recovery, subjective measures of motivation (1: 'poor', 2: 'OK', 3: 'good', 4: 'excellent'), fatigue (0: 'no fatigue' – 5: 'extremely fatigued') , and total quality of recovery (6: 'very poor' – 20: 'excellent')(Kenttä & Hassmén, 1998) were obtained using methods previously described by Fell et al. (2008) and Borges et al. (2018)(Fell et al., 2008; Borges et al., 2018). The total quality of recovery (TQR) scale was originally proposed by Kentta and Hassmen (Kenttä & Hassmén, 1998), and is analogous to Borg's rating of perceived exertion scale (G Borg, 1998).

Postural Stability

As far as we are aware based on the review reported in Chapter 2, only one study has investigated the effects of resistance training on postural control in the 72-hours following exercise in older adults (Naderi et al., 2021). It is acknowledged that any preliminary data collected on this topic would be exploratory, and is unlikely to be confirmed during this PhD, but may be interesting to present to fellow researchers should a strong association be found.

Postural stability was measured by the assessment of Centre of Pressure (COP) sway. Quiet stance COP sway was measured three times for 30 seconds at each time point. The mean of the three trials was calculated and used for statistical analysis. Participants stood on a Portable Force Platform (PASPORT Force Platform PS-2141, PASCO, US), with their feet shoulder width apart and their arms folded across their chest. When they felt ready, participants closed their eyes and informed the researcher. The researcher then started recording data using PASCO Capstone v2.5 at 100 Hz for 30 seconds. COP sway was assessed as the total path (mm) of displacement of the COP in the medio-lateral and anterior-posterior planes, using the following equations:

CoPy=350*([Force Beam 1 (N)]+[Force Beam 2 (N)])/[Vertical Force (N)]

CoPx=350*([Force Beam 2 (N)]+[Force Beam 3 (N)])/[Vertical Force (N)]

Dx=diff(1,[CoPy (mm)])

Dy=diff(1,[CoPy (mm)])

path=sqrt([Dx (mm)]^2+[Dy (mm)]^2)

TotalPath=sum([path (mm)])

Timed Up-and-Go

The Timed Up-and-Go test (TUG) is used as measure of functional mobility, gait, and falls risk (Avers, 2020). Currently, only two studies have previously reported the effect of resistance exercise on the TUG test in older adults (see section 2.4.3). Participants sat in a chair with their back against the chair back. On the start command, participants rose from their chair, walked 3-metres at a 'comfortable pace', turned at a cone, walked back to the chair, and sat down. Timing began at the instruction to start, and ended when the patient was seated. Participants performed this only once at each time point.

Five Chair Stands

The five chair stands test is used as a measure of functional lower extremity strength, balance, and falls risk in older adults (Bohannon, 2006; Guralnik et al., 1994; Csuka & McCarty, 1985). Participants sat in a chair with their back against the chair back. On the start command, participants rise from the chair, and sit down for a total of five repetitions. Timing began at the instruction to start and ended when the patient had returned to being seated for the fifth time. Participants performed this test only once at each time point.

4.3.9 Exit Survey

After completing the last study visit, participants were given the opportunity to complete an exit survey, either in the laboratory or in their own time at home (Appendix C). This online survey was hosted by onlinesurveys.ac.uk. In total, the survey featured 16 questions and sought to understand the experiences and opinions of the participants surrounding the laboratory study. There were three sections of the survey; (1) Acceptability of cow's milk as an exercise recovery supplement; (2) Awareness of, and attitudes towards, exercise recovery strategies; (3) Attitudes towards delayed onset muscle soreness. Questions pertaining to participant identification were included at the start of the survey.

The survey used a mixed-methods approach, combining free-text (open-ended) and multiple-choice questions. For some multiple-choice questions, participants were prompted to explain their answer in a free-text format.

4.3.10 Data Analysis

Data is presented as mean ± standard deviation unless specified otherwise. The primary outcome was maximal isometric voluntary contraction (MIVC). Secondary outcomes were perceived muscle soreness, perceived recovery, postural stability, timed up-and-go and time to five chair stands. Additional data is presented from an exit survey assessing the participants experience of the study and attitudes towards exercise recovery supplements.

One-way ANOVAs with Tukey post-hoc analysis were used to assess for group differences in participant characteristics, 24-hour dietary intake, and MIVC values during the familiarisation visit. Data were assessed for normality by Shapiro-Wilk test and visual inspection of box-plots. Mauchley's test was used to check the sphericity of the data. Mixed ANOVAs were used to assess for time and group differences for MIVC values, postural stability, TUG test, five chair stands, and muscle soreness. Mixed ANOVAs were also used for Likert style perceived recovery scales as recommended by Norman (2010), Sullivan & Artino (2013), and Harpe (2015), and as used for the same perceived recovery scales by Borges et al (2016)(Borges et al., 2016; Norman, 2010; Sullivan & Artino, 2013). We are aware that due to the very small sample size in this study, the p values reported are likely to be unreliable and should therefore be interpreted with caution.

Survey data were analysed by group for the section 'Acceptability of cow's milk as an exercise recovery supplement' and as a whole cohort for the following two sections. Answers given to multiple choice questions are reported as a fraction. Content analysis was conducted on responses to open-ended questions through a systematic classification process of coding to quantify the identification of words or concepts (Hsieh & Shannon, 2005). Data were read and re-read to ensure familiarisation and understanding, and interesting aspects of the data were highlighted that captured key concepts in relation to the pre-defined categories. Where more than one code could be derived from a singular free-text answer, codes are reported as a frequency.

4.4 Results

4.4.1 Participant Characteristics

Eleven older adults (n = 6 male; n = 5 female) were recruited to this study. One female experienced knee pain following the familiarisation visit and did not wish to continue with the study. Therefore, data is analysed on ten participants (n = 6 male; n = 4 female). Participant characteristics are presented in Table 4.2. There were no significant differences between groups for any of the participant characteristics or 24-hour dietary intake values ($p > 0.05$). Recruitment for this study was difficult, and hence, minimum sample size was not achieved.

Table 4.2 Participant Characteristics

Characteristics	Group		
	Whole milk (n=3)	**Skimmed milk (n=4)**	**Control (n=3)**
Sex	M (n=2); F (n=1)	M (n=2); F (n=2)	M (n=2); F (n=1)
Age (y)	80 ± 5	74 ± 4	73 ± 2
Body mass (kg)	74.3 ± 6.0	71.8 ± 11.8	67.9 ± 8.3
Height (cm)	166.4 ± 3.2	165.4 ± 13.4	173.1 ± 11.0
Average Peak Torque (Nm)	131 ± 78	127 ± 56	121 ± 33
RAPA Aerobic	6 ± 2	5 ± 2	6 ± 1
RAPA Resistance	1 ± 1	1 ± 1	1 ± 1
Leg Press 1-RM	62 ± 26	94 ± 9	72 ± 30
Knee Extension 1-RM	80 ± 30	81 ± 18	83 ± 25
Hamstring Curl 1-RM	75 ± 27	70 ± 20	78 ± 23
	24-Hour Dietary Intake		
Energy Intake (kcal)	1435 ± 335	1861 ± 625	1748 ± 379
Protein (g)	62 ± 44	77 ± 19	69 ± 29
Carbohydrates (g)	162 ± 82	231 ± 86	195 ± 31
Fats (g)	44 ± 12	63 ± 41	56 ± 8

Data presented are means ± SD. Characteristics were measured during familiarisation, 24-hour dietary intake was recorded for 24 hours prior to the exercise bout. M: male; F: female; y: years; kg: kilograms; cm: centimetres; Nm: newton metres; RAPA: rapid assessment of physical activity; 1-RM: one repetition maximum; kcal: kilocalories; g: grams.

4.4.2 Maximal Isometric Voluntary Contraction

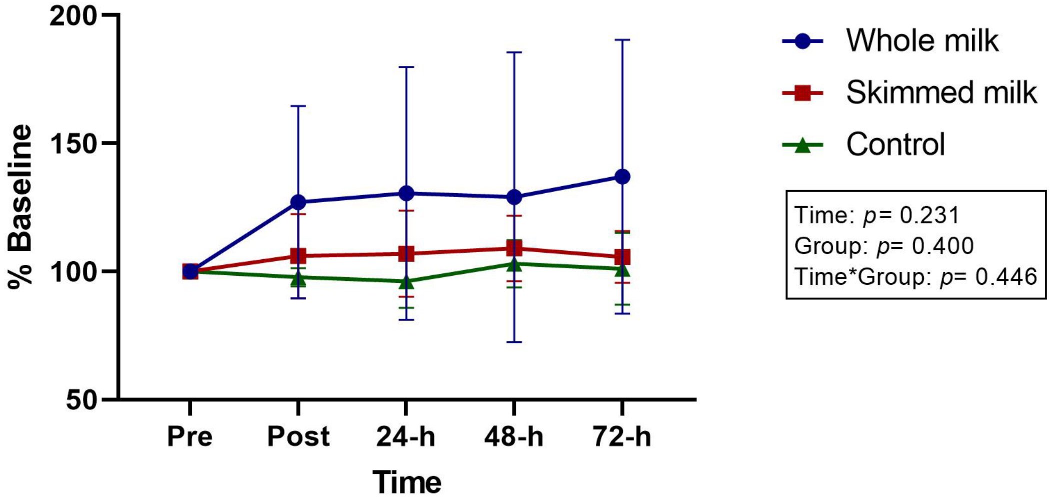

Figure 4.2 Maximal isometric voluntary contraction values before and following a resistance exercise session presented as a percentage of pre-exercise values ± SD of the change. Data were analysed using a mixed ANOVA. h: hours

Data for maximal isometric voluntary contractions (MIVC) of the knee extensors are presented as the average peak torque achieved over the four attempts at each time point (Figure 4.2). Absolute values for MIVC of the knee extensors were comparable between groups at baseline (Whole milk: 141.1 ± 87.7 N.m; Skimmed milk: 128.2 ± 66.9 N.m; Control: 139.8 ± 36.2 N.m; p= 0.961). Due to violations of sphericity, Greenhouse-Geisser corrections were applied when assessing percentage change from baseline. There was no significant effect of time on MIVC (p= 0.231), and no significant time*group interaction (p= 0.446).

4.4.3 Perceived Muscle Soreness

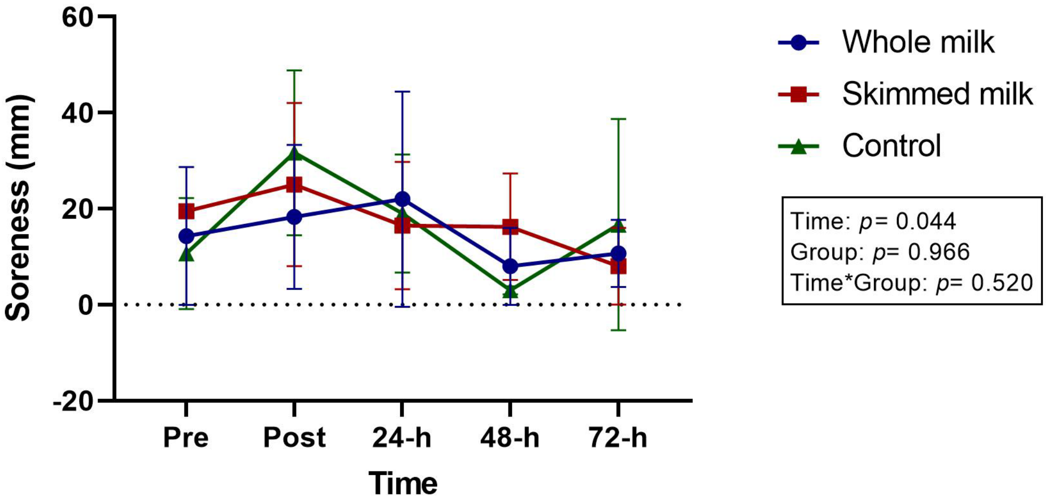

Figure 4.3 Perceived muscle soreness before and following a resistance exercise session (mean ± SD). Data were analysed using a mixed ANOVA with Bonferroni adjusted post hoc pairwise comparison. h: hours

Figure 4.3 shows groups means of muscle soreness throughout the study. There was no significant effect of group on perceived muscle soreness (p= 0.966). Mean baseline values for perceived muscle soreness were not significantly different between any groups (Whole milk: 14.3 ± 17.6 mm; Skimmed milk: 19.5 ± 1.7 mm; Control: 10.7 ± 14.2 mm), nor were they significant at any time point. Despite an overall significant effect of time F (4,28) = 423.733, p= 0.044, post-hoc tests revealed no significant differences between time-points. There was no significant time*group interaction (p= 0.520).

4.4.4 Perceived Recovery

Fatigue

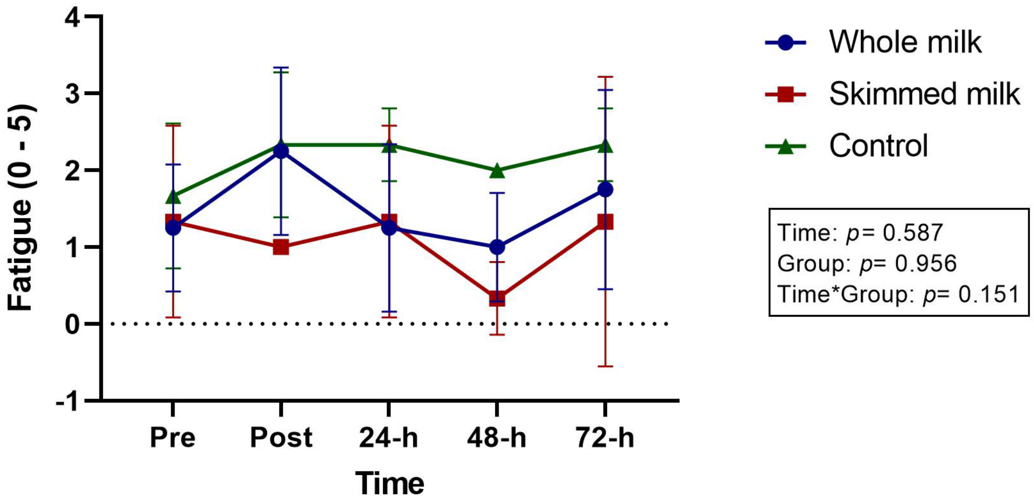

Figure 4.4 Perceived fatigue before and following a resistance exercise session (mean ± SD). Data were analysed using a mixed ANOVA. h: hours

Figure 4.4 shows changes in reported fatigue across the study. Reported fatigue did not change throughout the study ($p= 0.587$) and was not dependent on assigned recovery beverage ($p= 0.956$). There was no time*group interaction ($p= 0.151$).

Total Quality of Recovery

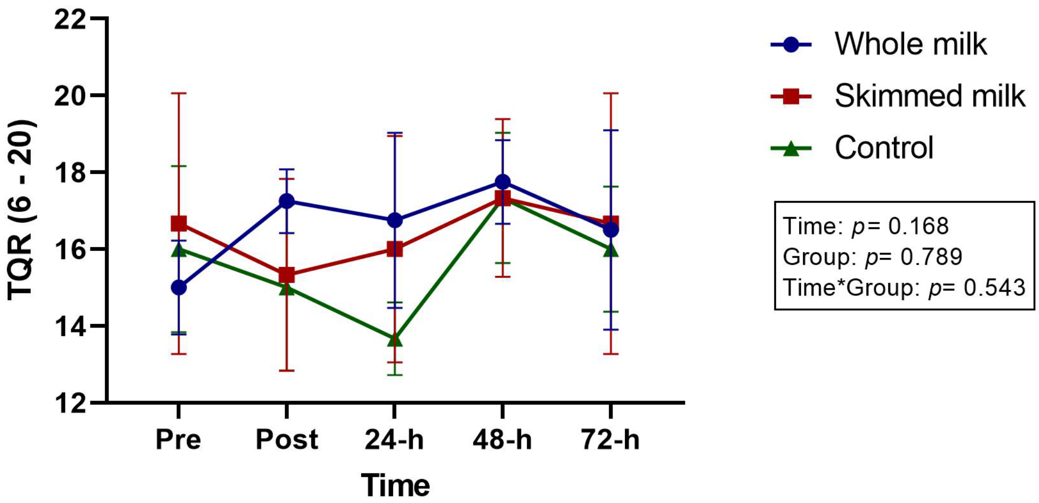

Figure 4.5 Perceived total quality of recovery before and following a resistance exercise session (mean ± SD). Data were analysed using a mixed ANOVA.TQR: total quality of recovery; h: hours

Figure 4.5 shows group changes in total quality of recovery over time. Perceived total quality of recovery was not significantly different between groups (p= 0.789) and did not change with time (p= 0.168). There was no time*group interaction (p= 0.543).

Motivation

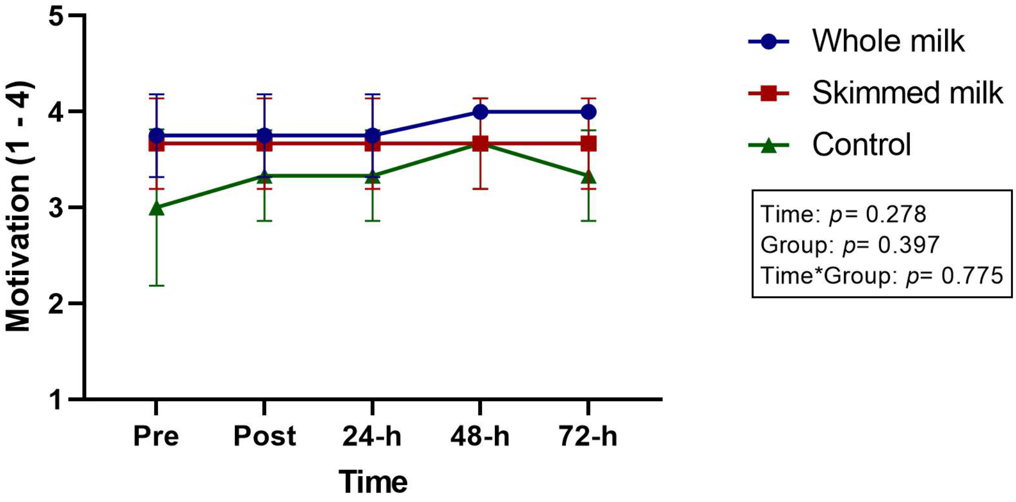

Figure 4.6 Perceived motivation before and following a resistance exercise session (mean ± SD). Data were analysed using a mixed ANOVA. h: hours

Figure 4.6 shows group changes in reported motivation at each time point. Motivation did not change over time (p= 0.278). There was no effect of recovery supplement on motivation (p= 0.397), and no time*group interaction (p= 0.775).

4.4.5 Postural Stability

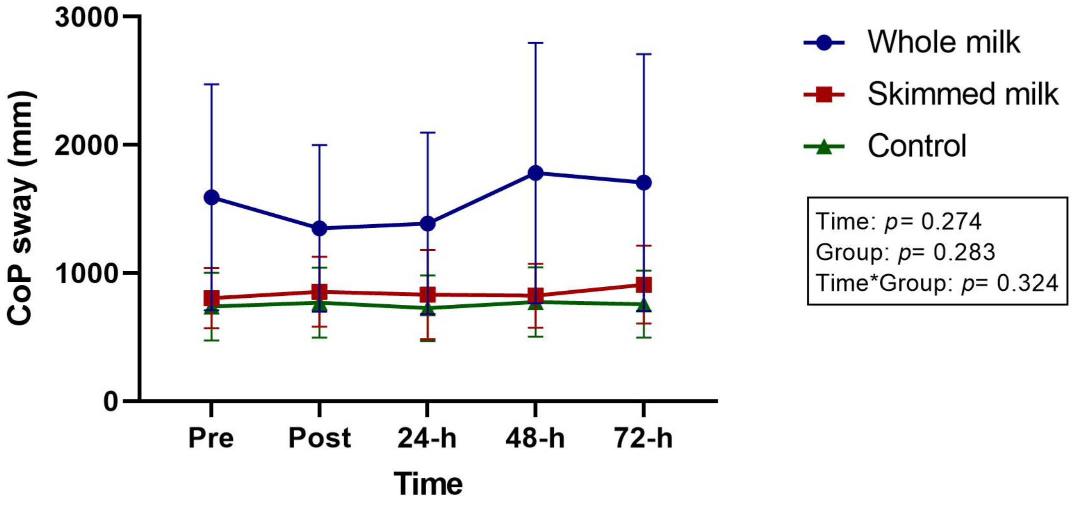

Figure 4.7 Postural stability measured by centre of pressure sway before and following a resistance exercise session (mean ± SD). Data were analysed using a mixed ANOVA. CoP: centre of pressure; h: hours

The mean of the three 30-second attempts at each time interval was calculated and taken as an individual value for analysis. These data are presented in Figure 4.7. There was no significant effect of group on centre-of-pressure (CoP) sway (p= 0.283). Greenhouse-Geisser corrections were applied to repeated measures analysis. CoP sway remained unchanged at each time interval (p= 0.274), and there was no time*group interaction (p= 0.324).

4.4.6 Timed Up-and-Go

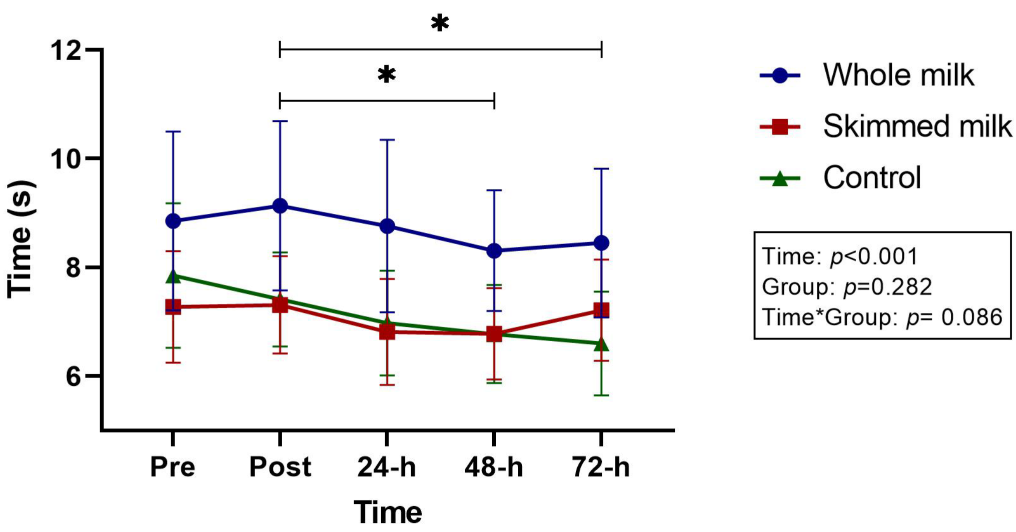

Figure 4.8 Time to complete the Timed Up-and-Go test before and following a resistance exercise session (mean ± SD). Data were analysed using a mixed ANOVA with Bonferroni adjusted post hoc pairwise comparison. h: hours

Mean times to complete the TUG test are displayed in Figure 4.8. There was a significant main effect of time on the time to complete the TUG test, F (4,28) = 9.178 ($p < 0.001$). Contrasts revealed that participants were quicker to complete the TUG test at 48-h (7.29 ± 0.36 s) and 72-h (7.42 ± 0.42 s) when compared with immediately post-exercise (7.95 ± 0.51 s, $p < 0.05$). There was no statistically significant difference between groups ($p = 0.282$), and no statistically significant time*group interaction $p = 0.086$).

4.4.7 Five Chair Stands

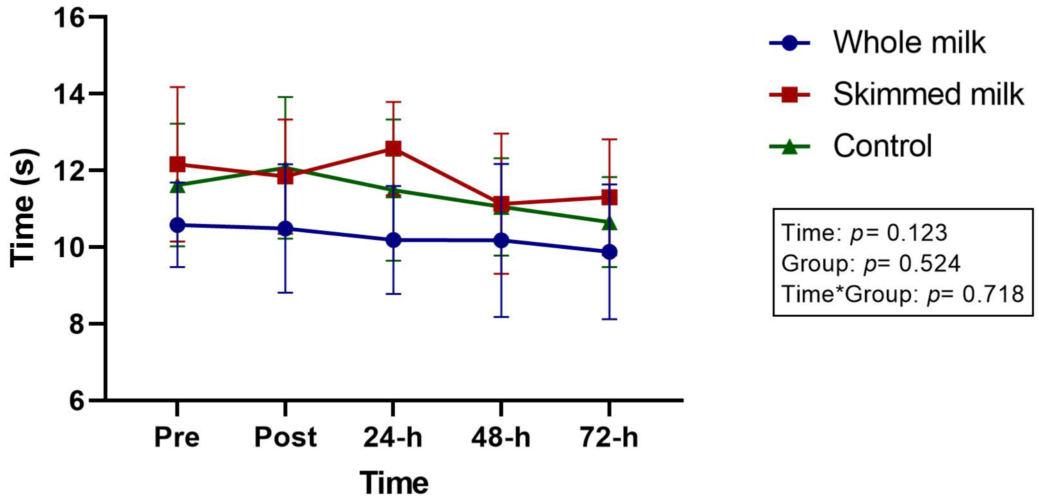

Figure 4.9 Time to complete five chair stands before and following a resistance exercise session (mean ± SD). Data were analysed using a mixed ANOVA. h: hours

Mean times to complete the five chair stands test are shown in Figure 4.9. Time to complete five chair stands was comparable between groups at all time points ($p = 0.524$), and did not significantly change as the study progressed ($p = 0.123$). There was no time*group interaction ($p = 0.718$).

4.4.8 Exit Survey

All ten participants completed the online survey after their final visit to the laboratory.

Acceptability of Cow's Milk as an Exercise Recovery Supplement

Table 4.3 General experience of consuming the supplement

	Positive	**Neutral**	**Negative**
Skimmed milk	3/4	1/4	0/4
Whole milk	3/3	0/3	0/3
Red grape juice	1/3	2/3	0/3

Data are presented as the proportion of individuals within each group

When asked about their general experience of consuming the supplement (Table 4.3.) responses were generally positive. Free-text responses revealed that two participants, one receiving skimmed milk and one receiving whole milk, found the volume of milk provided difficult to drink. The other five participants that received a milk drink gave positive statements such as 'enjoyed it', or 'found it no problem'. One participant receiving the juice found the volume difficult, one thought it too sweet, and another found it 'refreshing'.

When asked specifically about the volume of fluid they were asked to drink, three out of four that received skimmed milk, two out of three receiving whole milk, and two out of three receiving juice had no problem with the volume. One participant assigned to the juice condition had an issue with volume due to the amount of sugar it contained.

When asked about the taste of the drink they were given, two participants that had whole milk replied with a positive response (e.g. 'the taste was very much to my liking'). Two participants that had skimmed milk also replied positively (e.g. 'I liked the taste, particularly as the drink was served chilled'), and the other two replied with a neutral statement (e.g. 'It was what I expected it to taste like'). Two participants that received juice gave a positive statement (e.g. 'It was pleasant'), and one gave a neutral statement (e.g. 'like Ribena - palatable but not to be sought out'). Data is missing for one participant assigned to the whole milk group.

There were no reports of gastrointestinal (GI) discomfort from any participant that received skimmed milk or whole milk. One participant from the juice group experienced some GI discomfort as a result of their supplement. One participant from the whole milk condition changed their habitual diet as a result of consuming the supplement, as did one that received skimmed milk. There were no changes to habitual diet for those that consumed juice.

Table 4.4 Willingness to consume supplement in the future

	Yes	Maybe	No
Skimmed milk	3/4	1/4	0/4
Whole milk	2/3	0/3	1/3
Red grape juice	1/3	0/3	2/3

Data are presented as the proportion of individuals within each group

Participants were asked if they would be willing to consume their supplement regularly after exercise in the future (Table 4.4). One participant from the whole milk condition had reservations due to the volume of milk, as did one participant that received skimmed milk. Three participants assigned to skimmed milk, and one assigned to whole milk said they would be willing to consume the supplement if research showed it was beneficial. Two participants that received juice would not be willing to consume it in the future, citing concerns of sugar content.

Table 4.5 Do you think drinking 2 x 500mL regularly is feasible?

	Yes	Maybe	No
Skimmed milk	2/3	1/3	0/3
Whole milk	2/3	0/3	1/3
Red grape juice	1/3	0/3	2/3

Data are presented as the proportion of individuals within each group. *missing data for skimmed milk

When participants were asked if it was feasible to regularly consume 2 x 500 mL of their assigned supplement regularly, the majority of those receiving milk said yes (Table 4.5), giving reasons such as being happy with affordability and volume. Two out of three participants did not think it was feasible to regularly consume juice due to the high sugar content. One participant would prefer hot drinks to whole milk.

Awareness of, and Attitudes towards, Exercise Recovery Strategies

Four participants claimed they were already aware of the potential of milk as an exercise recovery strategy before participating in the study, but five were unaware of the potential use. One participant did not answer this question.

When asked to name other recovery strategies that they were aware of (Table 4.6), 'rest' was the most common, being mentioned on three occasions. Followed by rehydration, massage, and a hot bath. Other strategies that were named only once include 'deep breathing', 'vitamin supplements', 'muscle rubs', and 'beer'. One participant could not name any other recovery strategies. Six participants gave positive responses when asked their views on recovery supplements for older adults, and three gave a neutral statement (Table 4.7). One participant did not give their views on recovery supplements for older adults.

Table 4.6 Examples of known recovery strategies

Code	***n***	**Examples**
Rest	3	• 'Rest'
Rehydration	2	• 'Drinks like: plain water, isotonic drinks, re-hydrating drinks, also energy gels and so on.'
Massage	2	• 'Massage'
Hot bath	2	• 'Hot bath with Epsom salts'

Data are presented as the total frequency each recovery strategy was mentioned

Table 4.7 Views on recovery supplements for older adults

Code	***n***	**Examples**
Positive	6	• I think milk would be of great benefit as many elderly need extra calcium • Important and might encourage older adults to participate in exercise more • Bring them on, if well proven and not too onerous
Neutral	3	• I have never felt the need for them and therefore not explored using them but might use them if they make a significant difference • I don't think of them in relation to age. Just in relation to energy expenditure, re-hydration and muscle recovery etc.
Negative	0	

Data are presented as the number of participants providing each view. One participant did not give their views.

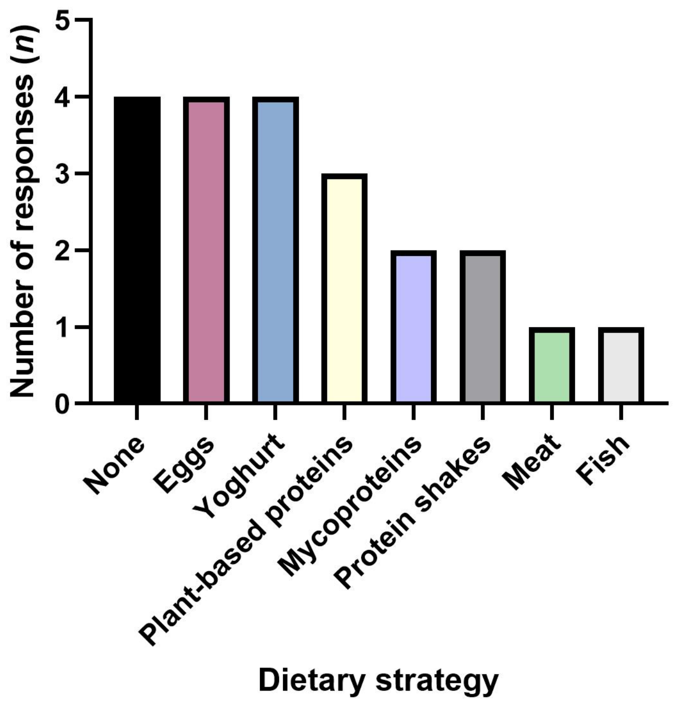

Figure 4.10 Dietary strategies deemed more acceptable than milk as a recovery supplement.

Participants were asked to identify any dietary strategy that they deemed more acceptable than cow's milk for use as a recovery strategy (Figure 4.10). Four participants declared that none of the options were more acceptable than milk. In descending order, the most commonly chosen recovery strategies deemed more acceptable than milk were eggs (*n*= 4), yoghurt (*n*= 4), plant-based proteins (*n*= 3), mycoproteins (*n*= 2), protein shakes (*n*= 2), meat (*n*= 1), and then fish (*n*= 1).

Attitudes towards Delayed Onset Muscle Soreness

No participants reported a change in habitual physical activity as a result of the exercise in this study. Reasons given for a lack of change can be found in Table 4.8. When asked if muscle soreness would discourage them from completing further exercise, six out of ten said it would 'to some extent' and four out of ten said it would not discourage them. No participant answered 'yes' to this question. Reasons for these responses are found in Table 4.9.

Table 4.8 Reasons for no change in habitual activity

Code	*n*	Examples
No soreness	4	• 'I did not feel any muscle pain'
Staying active	4	• 'I did experience some soreness in my legs but it did not stop me from going for a walk.'
No change	2	• 'No effect at all on my daily activities'

Data are presented as the number of participants providing each reason.

Table 4.9 Answers to, and reason given, to the question: 'Would you be discouraged from completing further exercise if you were experiencing muscle soreness?'

Answer	*n*	Examples
No	4	• 'It would have to be more than soreness to discourage me' • 'I think it is important to keep on with exercise and not give up'
To some extent	6	• 'Need to understand cause of soreness' • 'It would depend on the severity. There's a balance between doing further damage and manning up' • 'Gentle exercise can help to assuage muscle pain'
Yes	0	

Data are presented as the number of participants providing each answer.

4.5 Discussion

For the first time, we investigated the effectiveness of whole bovine milk for expediting exercise recovery, or attenuating muscle damage in older adults following resistance exercise, versus skimmed milk and a carbohydrate control drink. Additional data was also collected to assess the acceptability of milk as a recovery strategy, and to investigate attitudes towards recovery strategies and exercise recovery. Due to a difficult recruitment process, the study is not adequately powered to detect group differences, and hence, all results should be interpreted with caution, and no conclusions should be drawn as to the effectiveness of whole milk as an exercise recovery supplement. This study does, however, provide critical insight into best practices for conducting exercise recovery protocols in older adults.

Almost universally throughout the data, there is a lack of significant effect of time or group on outcome measure, with the exception of a time effect for the Timed Up-and-Go test. Although group differences were not expected due to the small sample size, the design and purpose of the study should have led way to some change in physical functioning or perceived muscle soreness in the days following resistance exercise, although the magnitude of which was unknown. There is a probable two-fold explanation for these results. Firstly, the statistical analysis for this study is heavily limited by the statistical power achieved due to a lack of participants, and secondly, the use of indirect markers of muscle damage that are regularly used in younger populations may not be as reliable in an older population.

As mentioned previously, this study was underpowered due to recruitment issues, recruiting only ten of the 36 participants needed for sufficient statistical power. This is a result of a variety of reasons, and all of them should be considered in any future research aiming to recruit older adults for similar studies in the United Kingdom. Firstly, the COVID-19 pandemic led to considerable delay in the piloting and launch of the study with recruitment finally commencing in March 2022 and ending in September 2022 due to time constraints associated with PhD funding. During this six-month period, only eleven older adults were recruited to the study, meaning only one participant was recruited every fortnight on average. Therefore, not only was the recruitment window limited, but recruitment within this was difficult. It cannot be said what effect COVID-19 had on older adults' willingness or ability to participate in this study approximately twelve months after the last national lockdown, but other studies have reported that participation rates are similar to those seen pre-pandemic (Tuttle, 2020), so this is unlikely to be a major contributing factor. Although no data was formally collected, anecdotal information suggests that it was the study design that deterred people from participation. For example, a number of individuals could not make the repeated study visits fit with their schedule, others did not want to drink cow's milk, and some did not want to complete resistance exercise, or already participated in resistance exercise. The pre-exercise health screening also limited recruitment numbers as individuals could not participate without the passing the PAR-Q+, a feat which becomes increasingly difficult with the prevalence of age-related health conditions. At present, it is unclear how these obstacles to recruitment could be overcome for such a study, given that these issues are integral to the study design. It is possible that similar studies may have to plan for a longer recruitment period in lieu of altering recruitment rate, or work collaboratively with other research centres to reach a wider population of people in order to achieve sufficient statistical power.

Intense or unaccustomed exercise is expected to cause EIMD characterised by losses of muscular strength, power, and muscle soreness (Doering, Reaburn, Phillips, Jenkins, et al., 2016; Owens et al., 2019; Clarkson & Hubal, 2002). Exercise recovery studies observe these perturbations in EIMD symptoms to indirectly assess levels of muscle damage and track recovery. However, in this study, there was no discernible effect of the prescribed exercise on measures of physical function, soreness, or perceived recovery. It is unclear if this is due to the resistance exercise causing no muscle damage and no fatigue, or an inability of the measurement tools to detect such a change in this scenario. It is possible that any decrements in physical functioning as a result of resistance exercise were masked by a learning effect in this population. Indeed, particularly when assessing the results of the whole milk and skimmed milk groups performing MIVC, values are higher than baseline in all time-points following exercise. It is possible that the older participants were still learning how to produce a maximal isometric contraction up to 72-hours, and this resulted in an apparent lack of change in maximal isometric strength following the resistance exercise. Indeed, even withstanding a lack of muscle damage, it is logical that MIVC would fluctuate around baseline values if there was no learning effect. Learning effects are common when assessing maximal strength and are usually prevented in data by the use of familiarisation before experimental visits (Morton et al., 2005; Symons et al., 2005). In younger adults, repeated repetitions of MIVC are generally recommended before a plateau is achieved in peak MIVC values (Meldrum et al., 2003), but the number of familiarisation visits required for older adults is unclear (Symons et al., 2004, 2005). This being said, the practicability of increasing familiarisation visits for similar studies in this population should be examined given that recruitment for this study was already slow.

It is not just MIVC values that showed no change following a bout of resistance exercise in this study, but also time to five-chair stands, postural stability, and perceived recovery. It would therefore be most logical to assume that the exercise protocol did not cause exercise-induced muscle damage in this study. However, since these outcomes have not been well used for assessing muscle damage in this population, it cannot be said with any certainty whether there was no muscle damage, or whether these outcomes are unsuitable as a marker of exercise recovery. For example, although centre of pressure (CoP) sway has been used in one study in older adults (Naderi et al., 2021) who saw a 45 % increase in CoP sway, it is not a well validated marker for exercise-induced muscle damage. Similarly, the perceived recovery scales used by both Borges et al (Borges et al., 2016), and Fell et al (Fell et al., 2008), saw changes over time in this measure, which the current study did not observe. These studies were both conducted in well-trained older adults, which speculatively, may indicate that the scales are not suitable for use in untrained older adults and may need further validation. Time to complete five chair stands has not previously been used as a marker of exercise recovery as far as we are aware. Like CoP sway and perceived recovery scales, more research should be conducted to assess the reliability and validity of this outcome for exercise recovery studies. More broadly, research should aim to identify any indirect markers of muscle damage that are both relevant and reliable in older adults that can be used in future studies.

Time to complete the TUG test saw a statistically significant effect of time, but the changes were contradictory to what would be expected. TUG speeds were significantly faster at 48- and 72-hours after exercise, compared with immediately post-exercise, which could indicate a learning effect. The expectation would be for individuals to take more time to complete the test if muscle damage were present, as previous studies have shown a 2-18 % (Orssatto et al., 2018; Naderi et al., 2021) peak increase in time to complete the test. Again, it is unclear why this study did not observe a 'normal' response, but this may be due to it not being a maximal test, and therefore once participants were well accustomed to the procedures they may perform it quicker due to familiarity. Generally, the TUG test has a high repeatability in older adults (*r*= .90-.97)(Morris et al., 2001; Smith et al., 2016), but it is unclear from the published studies if participants had already undergone significant familiarisation to obtain these values. These studies also do not appear to investigate temporal effects, for example, one study evidenced a high reliability for the TUG test (*r*= .960), but the mean times to complete the TUG test reduced consistently each day for five days, resulting in a difference between day one and day five of 0.82 s (~8 %) (Smith et al., 2016). If this variation is also present in our study, it may explain the significant decrease in time to complete the TUG test from post-exercise to 48- and 72-hours, whilst not discrediting the previous studies that have shown an effect of muscle damage (Orssatto et al., 2018; Naderi et al., 2021). It has been recommended that older adults may need 4-5 familiarisation attempts to achieve a stable baseline measure (Namsawang, J. and Muanjai, 2021). Therefore, the TUG test remains a valid diagnostic tool for assessing the physical capability of older adults, but its use in muscle damage studies may need to be deferred until such a time that estimates of repeatability over several days can be obtained.

There was also a significant effect of time on perceived muscle soreness, although post-hoc tests did not reveal any significant difference between individual time points. The highest values for perceived muscle soreness were immediately post-exercise, and pre-exercise values were higher than 48- and 72-hours post-exercise. Generally, individuals will experience no muscle soreness when they are rested, and soreness will peak 24-48 hours after unaccustomed exercise (Owens et al., 2019). The relatively high pre-exercise values indicate that, although visual analogue scales are widely used for assessing perceived muscle soreness, older adults in this study may have misunderstood what was meant by muscle soreness. Indeed, as previously discussed in Section 3.5.4, older adults generally did not understand the concept of delayed onset muscle soreness, and often mistook it for injury. This issue may be mitigated in two ways. Firstly, a brief summary of delayed onset muscle soreness could be provided to individuals before the completing of any visual analogue scales, or alternatively via assessing the pressure pain threshold of participants, which would limit any variation caused by misunderstanding. The latter has not previously been used in untrained older adults for muscle damage studies, and so may require some validation.

Of course, in spite of the aforementioned limitations in the outcome measures, it is also entirely possible that the participants in this study did not experience exercise-induced muscle damage. The exercise protocol that was used (four sets of ten repetitions at 70% 1-RM of three lower limb exercises; leg press, knee extensions, and hamstring curls) should have been a significant stimulus to produce exercise-induced muscle damage in older adults (Nikolaidis, 2017; Naderi et al., 2021), whilst attempting to replicate what would be considered a 'usual' resistance exercise session for older adults. However, this protocol was not directly replicated from any previous studies, and so it is hard to define the suitability of the exercise session for this study. As these were untrained older adults it is also hard to verify if their estimated 1-RM was a true reflection of their physical capability. Hence, it is possible that some individuals had their 1-RM underestimated. This would make the exercise protocol relatively easier for some of the participants, and may explain a general lack of EIMD in this population. Other studies (Przybyla et al., 2006; Orssatto et al., 2018) in older adults have previously completed sets of exercises to failure in order to ensure all participants reach volitional exhaustion, and use this as a benchmark to standardise relative load across the population. This may be a good solution for further work, but again would require an estimation of 1-RM and would likely be subject to an individual's motivation to exercise. Of course, it is also possible that there was some evidence of a repeated bout effect following the familiarisation visit, although this study did not track any markers of EIMD to confirm or refute this. If present, this may have reduced the magnitude of damage from our exercise protocol, although every effort was made to minimise this possibility whilst still being able to estimate similar relative training loads for all participants.

The exit survey administered on cessation of the study has provided information that is complimentary to the findings in Chapter 3. Indeed, this data adds the viewpoint of older adults that have already completed a resistance exercise session, and consumed milk as a recovery aid. The main finding of this survey is that the majority of participants that consumed milk found the general experience to be positive. The milk was found to be palatable, there were no reports of gastro-intestinal issues, and only one participant altered their diet as a result of the supplement. However, when probed further, there were issues with the volume of milk they were being asked to drink (2 x 500 mL), with the majority of participants believing it was too much. Despite this, most of the participants (5/7) said they would be willing to consume the supplement in the future. These findings are similar to those seen in the MIlkMAN study, which aimed to assess the feasibility and acceptability of a six-week milk and resistance exercise intervention in older adults (Granic, Hurst, Dismore, Stevenson, et al., 2020). In this study, over 80 % of participants said that consuming 2 x 500 mL of milk after exercise, twice per week, was easy or very easy, and none found it difficult. Only two out of seventeen participants reported that the volume of milk was 'somewhat' a barrier, with all other participants claiming it was 'not at all' a barrier. Whilst these results are promising for the acceptability of milk, it should be remembered that only those that are already willing to drink milk volunteered to participate in these studies, and therefore, the actual acceptability to the general population is likely to be lower as previously evidenced in Chapter 3 (Hayes et al., 2021).

When participants were asked if any of the listed whole foods would be more acceptable than milk as an exercise recovery strategy, 40 % said no, milk was the most acceptable. Eggs and yoghurt were indicated to be more acceptable by 40 % of the participants, with plant-based proteins (30 %) and mycoproteins (20 %) following in popularity. This suggests that whilst milk is a good candidate for use as an exercise recovery aid, it is also worth investigating the efficacy of other high-protein whole foods, or specifically other dairy products such as yoghurt for aiding exercise recovery. The relatively high popularity of plant-based proteins and mycoproteins should also not be ignored given the current climate, and may present an avenue for future research to identify an exercise recovery aid for those with ethical or environmental concerns. Mycoproteins especially have already been shown to stimulate muscle protein synthesis to higher rates than a leucine-matched bolus of milk protein in young men (Monteyne et al., 2020), although this is yet to be translated to the exercise recovery literature in either young or older adults.

As was also observed in the online survey data (see Section 3.4.5) the most commonly named recovery strategies that participants were aware of were heat treatments, massage, and rest. However, unlike the online survey, participant's attitudes towards exercise recovery supplements were largely positive (60 %) with no individual presenting a negative view. This is dramatically different to the online survey, where only 7 % of respondents gave a positive review of recovery supplements, and 49 % presented a negative view. With some speculation, this difference could be explained simply by participation in the study. The participant information sheet that was given to participants, and their participation in the study, is likely to have educated them on whole foods being an exercise recovery supplement. Survey respondents did not have this and negative opinions generally surrounded the idea that supplements were manufactured and therefore a 'money-making scheme', whereas positive opinions of study participants commonly referenced the benefits of milk. Going forwards, it may be important to distinguish manufactured supplements from whole foods when discussing exercise recovery supplements to ensure that the participant and research team are clear on what is being asked.

None of the participants in this study experienced a change to their habitual daily activity as a result of muscle soreness from the study, with the most common reasons for this being either that they did not experience soreness (n = 4), or that they wished to stay active regardless of muscle soreness (n = 4). A greater number of participants said that muscle soreness may prevent them from completing further exercise 'to some extent' (n = 6), but again, no individuals said it would discourage them completely. These numbers are slightly lower than the online survey data provided, but speculatively, this could be due to the participants already being motivated to exercise as evidenced by their participation in the study.

4.5.1 Strengths and Limitations

A main strength of this study is that it aimed to assess the effectiveness of milk as an exercise recovery aid using a mixture of both traditional measures of muscle damage, and assessments of physical function that would be relevant to an older adult. This study also incorporated an exit survey within the study design, gathering invaluable information on not just the efficacy of the supplement, but also the acceptability of the supplement to an older population should it prove to be beneficial. The main limitation of this study is a sample size that was not sufficiently powered for robust statistical analyses. Ideally, recruitment for this study would have continued until the appropriate sample size was achieved. However, as is the nature of PhD studies, time limitations dictated a recruitment end date. It is also unclear if no exercise-induced muscle damage was caused, or if the methods used were insufficient for detecting such a change in this population.

4.6 Conclusions

In conclusion, this chapter could not answer to the effectiveness of milk as an exercise recovery aid in older adults. However, it does provide food for thought for progressing research surrounding exercise recovery in older adults by discussing various methodological and applicability considerations. Importantly, the results of this study may act as a springboard for future studies in this area looking to validate markers of exercise recovery in older adults or identify new acceptable nutritional interventions for these individuals.

Chapter 5 : General Discussion

5.1 General Discussion

The research presented in this thesis examined what we know about recovery from resistance exercise in older adults. More specifically, this thesis outlined the state of the current literature surrounding exercise recovery in older adults and began to explore the efficacy and acceptability of whole food interventions for optimising exercise recovery in this population. Optimising recovery from resistance exercise in this population should be considered of great importance in order to achieve maximal adaptation and reduce the risk of any adverse side effects of muscle damage. This thesis also included data on older adults' motivators and barriers for participating in resistance exercise and their knowledge and attitudes towards exercise recovery. Together, this knowledge could inform considerations for exercise prescription and recovery interventions in older adults. This chapter will contemplate and synthesise the findings from Chapters 2-4 and discuss how they relate to current knowledge in the field before recommending avenues for future research and practical recommendations that have been highlighted by this body of work.

5.2 Reflection on Main Findings

5.2.1 What We Know About Recovery from Resistance Exercise in Older Adults

Prior to this thesis, there has been no detailed overview of the literature surrounding recovery from resistance exercise in older adults. Data from Chapter 2 highlight that research assessing exercise recovery and exercise-induced muscle damage in older adults is not only sparse, but also inconsistent in study protocol and findings.

In 2020, a narrative review aimed to collate the literature assessing the effect of age on exercise-induced muscle damage (Fernandes et al., 2020), but failed to acknowledge a large proportion of the literature that did not include a younger comparison group. Chapter 2 assessed a wider range of research in an attempt to identify every marker of exercise-induced muscle damage (EIMD) that had been reported to better characterise the exercise recovery process in older adults. From this, a comprehensive overview of the literature was compiled that organises data by themes and highlights gaps in our current knowledge. The findings from Chapter 2 echo those from Fernandes et al., who concluded the theory that ageing hampers exercise recovery may not be supported by the literature, and that contradictory to this belief, EIMD may actually be less severe in older men (Fernandes et al., 2020). However, mechanistic data to suggest why this may occur could not be identified. This thesis could not make any recommendations regarding the effect of age on exercise recovery in older females due to a very limited number of published studies and a lack of repeated measurements of EIMD markers.

A range of indirect markers of EIMD was identified from the literature surrounding exercise recovery in older adults. The most consistent of these markers was muscle soreness, which reported peak changes at 24-48 hours in most of the published studies which is a similar time-course to younger adults (Owens et al., 2019). However, discrepancies in the measurement scales used made it hard to determine values for a magnitude of change. Conversely, no clear consensus could be made on the effect of muscle damaging exercise on physical function in older adults despite fourteen studies reporting the outcome. This is largely due to a lack of studies observing full recovery, a lack of uniformity with time points for specific outcome measures, and differing exercise protocols. Very few studies reported markers of physical function that are deemed to be relevant to older adults such as falls risk, chair stands, and timed up-and-go tests. This presents a blind spot in current knowledge and would be useful data to determine how older adults acutely respond to resistance exercise in a real-world setting. Perhaps somewhat unsurprisingly, no deductions could be drawn from the breadth of studies that reported the immune response to resistance exercise or the presence of circulating muscle proteins such as CK and Mb, and it is suggested that their usefulness in quantifying recovery status in older adults may be restricted. An important omission from the current literature is the exploration of recovery strategies for older adults. Only one paper was identified in Chapter 2 that sought to assess the efficacy of recovery strategies (cold water immersion and massage) in older adults (Naderi et al., 2021). No studies were found that have used nutrition as a means to aid recovery from resistance exercise in older adults. A similar paucity of literature was found by a narrative review discussing nutritional and pharmacological interventions in older adults (Clifford, 2019), but in slightly younger adults (52-66 years) following a range of exercise protocols.

5.2.2 The Need to Optimise Research Assessing EIMD in Older Adults

Chapter 4 attempted to rectify some of the gaps and inconsistencies in the literature that have been emphasised in the previous section. For example, not only was it the first study to assess the effectiveness of a nutritional intervention for aiding recovery from resistance exercise in older adults, the study also included markers of physical function that may be more relevant to older adults such as chair stands and postural stability, whilst employing a resistance exercise protocol that resembled a usual training session for older adults. Whilst this study design was conceived as a result of various conscious decisions to make the protocol as ecologically valid as possible it is likely this added too much noise to the data for any conclusions to be made, especially given the relatively small sample size that could be recruited. What this study did achieve however, is to highlight the need for optimising exercise recovery research in older adults. Indeed, further consideration needs to be given to the apparent learning effect observed across almost all measures of physical function in Chapter 4. For example, it has previously been shown that older adults are more variable in their ability to perform maximal voluntary contractions, and need more practice and familiarisation to achieve similar consistency to younger adults (Rozand et al., 2020). It is not immediately clear how this could be rectified given the participant burden that extra familiarisation visits, the recommended and most obvious option, could create (Hurst et al., 2018). Similarly, the exercise protocol used in Chapter 4 may not have been sufficient to cause muscle damage severe enough to be detected by our chosen markers of EIMD or to overcome the learning effects previously discussed.

Therefore, before looking to identify the effects of interventions on exercise recovery in older adults, it may be prudent for considerable research to be conducted first to identify, validate, and standardise markers of EIMD that are specific to older adults, and then to characterise their usual response to various exercise protocols. As previously mentioned, the majority of the literature included in Chapter 2 uses the same markers of EIMD traditionally used in younger adults. The data in this thesis illustrate that the use of visual analogue scales for assessing muscle soreness has been extensively and successfully used in older adults, and there appears to be no issue in continuing to do so on the condition that scales are standardised across studies. However, there was little uniformity in measures of physical function across the studies, and data from Chapter 4 suggests there may be a learning effect for these measures. Therefore, a potential alternative to using maximal voluntary contractions for assessing muscle strength which is currently used in the majority of studies reporting physical function measures might be to employ methods such as the twitch interpolation technique. Considering that the twitch interpolation technique is involuntary, this would ensure the resultant contraction was devoid of any learning effects. Additionally, this would provide some mechanistic insight by helping to quantify levels of voluntary activation to determine the origins of muscle function changes after muscle damaging exercise. Equally, the limited applicability of maximal voluntary contractions to a sporting context in younger adults has resulted in a growing number of studies seeking to quantify the effects of EIMD in more sport-specific movements. Such markers include countermovement jump height or bench ball throw distance (Byrne & Eston, 2002; Bartolomei et al., 2019). We propose that like younger adults, specific markers of muscle function should be used that are relevant to older adults. Chapter 4 employed methods such as the timed up-and-go test and centre of pressure sway (postural stability) that have previously been used in studies of older adults (Naderi et al., 2021; Orssatto et al., 2018), but found no effect of muscle damaging exercise. In spite of this, there remains promising evidence that these methods could be used to characterise exercise recovery in older adults subject to validation. Additional age-specific markers that have been used include stair ascents, stair descents and hand-grip strength (Orssatto et al., 2018; Marques et al., 2019), and again, these should be considered for future research alongside any novel markers that show promise.

5.2.3 Acceptability and Efficacy of Whole Food Interventions for Exercise Recovery

As discussed in Chapter 2, there are currently no studies aiming to identify nutritional interventions for exercise recovery in older adults despite their potential to aid recovery from muscle damaging exercise (Davies et al., 2018; Bowtell & Kelly, 2019; Clifford, 2019). Therefore, Chapter 3 aimed to identify the attitudes of older adults towards supplements and whole foods as strategies for aiding recovery from resistance exercise to ensure acceptability and adherence if found to be effective. Following this, Chapter 4 aimed to establish the efficacy of milk for aiding exercise recovery and to gather further data on the acceptability of milk from the perspective of individuals that had experienced the intervention.

Nutrition was rarely mentioned as a recovery aid that older adults used or were aware of in Chapter 3, but nutrition was also not mentioned when the same question was asked to study participants in Chapter 4. More commonly known recovery strategies were massage, rest, and heat treatments. Therefore, before discussing the acceptability and efficacy of whole foods it should be acknowledged that older adults may require education as to the benefits of nutrition for exercise recovery. That being said, whole foods were thought to be more acceptable than supplements by 80 % of older adults, indicating a clear preference for 'natural' and 'healthy' recovery aids. Interestingly, cost and accessibility were also mentioned to be a benefit of whole foods compared with supplements, which supports our belief that recovery strategies should be readily available. Therefore, although supplements may be effective for improving recovery, their uptake in older adults is likely to be poor, whereas whole foods are viewed more positively.

This thesis specifically aimed to establish the acceptability and efficacy of cow's milk following studies that evidenced its efficacy for exercise recovery in younger adults (Cockburn et al., 2008, 2012; Rankin et al., 2015). It is thought that milk may be particularly suitable for older adults due to the nutritional composition, specifically the high protein content, alongside the wide availability, low cost, and relatively smaller appetite effects compared with other foods (James, Stevenson, Rumbold, et al., 2019; Law et al., 2017; Brown et al., 2016). Milk was generally deemed to be an acceptable recovery strategy by survey respondents in Chapter 3, and this was supported by data in Chapter 4 from older adults that had consumed milk for the study intervention. However, there remains concerns around the total volume of milk that is required to meet the recommended dose of protein thought to elicit a beneficial effect. Indeed, two servings of 500 mL may need to be consumed in older adults which could be considered too great a quantity for some individuals (Holwerda et al., 2019; Cockburn et al., 2012; Granic, Hurst, Dismore, Stevenson, et al., 2020). Despite this, most study participants said that they would be willing to consume the supplement for exercise recovery in the future. This is similar to findings from the MIlkMAN study who asked participants to consume 2 x 500 mL of milk after every resistance exercise session twice per week for six weeks (Granic, Hurst, Dismore, Stevenson, et al., 2020). In this study, only two out of seventeen participants reported that the volume of milk was 'somewhat a barrier'. However, the general acceptability of milk should not be confused for preference over other whole foods. In participants that completed the experimental study in Chapter 4, only 40 % said milk was the most acceptable whole food recovery strategy, with eggs and yoghurt being preferred by 40 % of the other participants, and plant-based proteins by 30 %. This suggests it is also worth investigating the efficacy of other widely available whole foods for improving recovery from resistance exercise in older adults. Likewise, this thesis has focussed on protein-rich whole foods but polyphenols may also aid exercise recovery (Bowtell & Kelly, 2019), and provide further promising avenues for optimising exercise recovery in an older population.

It is hard to comment on the efficacy of milk as an exercise recovery strategy as a result of the data presented in this thesis. Despite the evidence that milk improves exercise recovery in younger adults (Cockburn et al., 2008, 2012; Rankin et al., 2015), the small sample size and seeming lack of EIMD reported in Chapter 4 does not allow for conclusions to be drawn either for or against the effectiveness of milk. Although recruitment for these types of studies is likely to remain difficult, the statistical power of this study could have been increased were only two groups (milk and isocaloric control) used rather than three. In hindsight, the first aim should be to determine the effects of milk for exercise recovery, and if this is supported by the evidence, then comparisons can be made between milk drinks with different fat contents. Similarly, the decision to use a more ecologically valid exercise protocol than other intervention studies may be considered to be controversial as this may be the reason that no EIMD was confirmed in Chapter 4. From this concern emerges considerations for future research. If a study is aiming to test the efficacy of an intervention as in Chapter 4, an exercise protocol that has previously been shown to induce significant muscle damage may be preferable so that the intervention has scope to provide measurable benefit. However, it could also be argued that if a 'normal' resistance exercise session does not induce measurable muscle damage, then there is no indication that an intervention would provide any meaningful benefit over passive recovery. Therefore, when designing research that assesses recovery interventions for EIMD in older adults the aims of the study should be carefully considered before an exercise protocol is chosen.

5.2.4 Encouraging Adherence to Resistance Exercise

First and foremost, increasing the participation of older adults in resistance exercise is essential. To achieve this, two hurdles need to be overcome; increasing the uptake of resistance exercise in older adults, and ensuring continued engagement beyond the initial sessions or programme. Data from Chapter 3 presents the motivations and barriers to older adults performing resistance exercise before discussing their knowledge and attitudes towards exercise recovery and how this might impact participation. Chapter 4 provides additional information surrounding the study participants' attitudes towards delayed onset muscle soreness.

As found in recent systematic reviews, data from Chapter 3 suggests that there appears to be misconceptions that older adults cannot safely perform resistance exercise (Gluchowski et al., 2022; Cavill & Foster, 2018). The main barrier to resistance exercise found by this thesis was physical health, with survey respondents often citing pre-existing medical conditions that were perceived as preventing them from participation. However, reassurance from a clinician that resistance exercise was safe was also seen as a motivator for resistance exercise. Likewise, over two thirds of survey participants claimed that they if they were experiencing muscle soreness, they may be discouraged from completing further exercise until the pain had subsided. This presents interesting arguments both for expediting recovery from resistance exercise in older adults, and providing them with the knowledge that muscle soreness is a result of the adaptation process, and not due to excessive exercise or exercising incorrectly as was another common misconception. Indeed, for the first time, the data in Chapters 3 and 4 provide some evidence to support the claim from Hurst et al. (2022) that there may be a need to educate older adults that post-exercise muscle soreness is a normal response to resistance exercise in order to ensure continued adherence (Hurst et al., 2022).

5.3 General Strengths and Limitations

This is the first body of work that aims to comprehensively assess recovery from resistance exercise in older adults. The multidisciplinary approach of this thesis provides perspectives that could not be gained through randomised controlled trials alone to create a clearer overview of what is already known, and the most important areas for future research. Nevertheless, there are limitations to this work that merit acknowledgement. Firstly, whilst the systematic scoping review is designed to identify gaps in the current evidence base of an area of research that is complex, or has not been reviewed comprehensively before, it is not designed to provide answers to specific research questions nor to assess the quality of the included studies. The findings from this scoping review can therefore only be interpreted to be a summary of the wider literature, and cannot be used to conclusively characterise the exercise recovery process in older adults. Secondly, the use of an online survey platform allowed high numbers of participants to be recruited, but this came at the expense of allowing researchers to probe for further information. Further, the use of an online survey likely excluded the oldest old, those from lower socio-economic backgrounds, and some minority ethnic groups. A self-selection bias was also likely to be present for this survey, and may have preferentially recruited older adults with interests in health and exercise. This could also be said for the participant recruitment process for the milk intervention study, and was illustrated by their relatively high physical activity status. This recruitment bias may also be shown by the difficulty that the study had in recruiting people that were previously untrained, as anecdotally, those that were not keen to participate did not generally buy in to the importance of resistance exercise for older adults, and vice versa. This will be a concern both for future research, and for encouraging older adults to participate in resistance exercise. The data collected in Chapter 4, and possibly also in the majority of studies included within the scoping review may therefore not be representative of minority groups, or older adults that are not already physically active.

5.4 Implications for Future Research

The data presented in this thesis provides an overview of what we already know about recovery from resistance exercise in older adults and provides preliminary data on the acceptability and efficacy of milk as an exercise recovery strategy. Before any conclusions can be made, and before recommendations can be made for best practice following resistance exercise, a substantial body of future work is required. The optimisation of research design for studies assessing exercise recovery in older adults is essential and has the potential to improve the certainty of findings, as well as allowing more direct comparison across the whole literature. This includes the validation of markers of EIMD in older adults that are both relevant to the population and consistent across study visits. Following a series of well-designed and comparable studies, it can then be determined if ageing hampers exercise recovery, or if this theory is refuted as concluded by previous work (Fernandes et al., 2020). It is the author’s opinion that oestrogen may have a protective effect from EIMD in females (Thompson et al., 2020), and hence, the paucity of literature reporting on EIMD in older females represents a distinct gap in our knowledge. Additionally, the identification of efficacious and acceptable whole food recovery interventions for older adults remains an important avenue for future research. However, before further work is done to identify optimal recovery strategies for older adults after resistance exercise, there is a distinct need to better characterise the EIMD response in older adults. This would ensure that any studies aiming to assess the efficacy of any strategy are well-designed in terms of outcome measures, and that they are also best-placed to detect differences to the recovery process that are meaningful to the individual, such as reducing falls risk if indeed this is a concern. With that being said, although milk has been shown to be effective, there is no need to focus research efforts on one food stuff, especially given older adults possible preference for alternative protein sources (Chapter 4). Finally, given the importance currently being placed on resistance exercise for the prevention of sarcopenia (Hurst et al., 2022), research should not forget that these benefits cannot be achieved without continued engagement in resistance exercise programmes. Hence, any research seeking to characterise exercise recovery or recovery interventions in this population should actively seek the opinions of older adults to ensure research aims align with their concerns and preferences.

5.5 Implications for Practice

The findings from this thesis can be used to inform practical recommendations for resistance exercise in older adults. For example, to increase uptake and maintain adherence there is a clear need to educate older adults on the benefits of resistance exercise and confirm safe participation for their age group. It may also be necessary to educate older adults that muscle soreness is considered a normal process in resistance exercise adaptation, and that the presence of this soreness is not considered to be caused by excessive exercise. From the data collected in this thesis there is also little evidence that there is impaired or delayed recovery from resistance exercise in older adults, but there is currently not sufficient literature to conclude either way. For now, it is likely that exercise practitioners can schedule training in a similar manner to younger adults, and according to meta-analyses that recommend 2-3 sessions per week for optimal gains in muscle strength and mass (Borde et al., 2015a; Steib et al., 2010; Murlasits et al., 2012). However, there remains the possibility that older adults with lower baseline muscle function could be at risk of increased falls or difficulty performing activities of daily living as a result of substantial muscle damage. Again, there is not enough data to prove this to be the case, but it may be indicated for practitioners, family members, and the individual themselves to be aware of the potential side effects and alter exercise plans accordingly if this becomes a problem. Likewise, although this thesis has been unable to shed any light on the efficacy of milk as recovery aid, alongside other high protein foods it has already been shown to optimise adaptation to resistance exercise programmes and be beneficial for overall health (Hartman et al., 2007; Josse et al., 2010; Granic, Hurst, Dismore, Aspray, Stevenson, Miles D. Witham, et al., 2020). On this basis, individuals may wish to consider regular milk consumption alongside a resistance exercise programme regardless of the effect it may exert on EIMD and exercise recovery.

5.6 Conclusions

The work in thesis aimed to establish why recovery from resistance exercise matters, what we know about it, and if any intervention strategies could be identified that were both effective and acceptable in older adults. Using a multi-disciplinary approach, this thesis demonstrates that despite resistance exercise being highly recommended for maintaining muscle health, the literature surrounding recovery from resistance exercise is currently lacking in strength and coherence, and that there is a distinct need to standardise research aiming to characterise EIMD and exercise recovery in older adults. The data collected for this thesis were unable to determine the effectiveness of milk as an exercise recovery aid, but it was found to be generally acceptable to older adults, and it is therefore recommended that future research continues to pursue this using more robust study designs.

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Appendix A: Search Strategy

Search Strategy

We will systematically search the following electronic databases for studies: MEDLINE, Scopus, Embase, SPORTDiscus and Web of Science. In addition, reference lists of all identified articles will be screened for additional studies.

The search strategy will include terms related to the population of interest (i.e. adults, older adults, elderly) in combination with the exercise mode (i.e. resistance training, weight training, weight-lifting, resistance exercise) and the outcomes of interest (i.e. muscle damage, exercise recovery, muscle soreness, muscle function, muscle strength, isometric strength, creatine kinase, inflammation, perceived recovery).

Web of Science

Set	Results	Save History / Create AlertOpen Saved History
# 4	1,911	#3 AND #2 AND #1 *Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI Timespan=All years*
# 3	2,520,258	**TOPIC:** ("muscle dysfunction" or "exercise induced muscle damage" or "muscle damage" or "muscle soreness" or "exercise recovery" or "fatigue" or "recovery" or "creatine kinase" or "myoglobin" or "Doms" or "responses") *Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI Timespan=All years*
# 2	2,205,461	**TOPIC:** ("older adults" or "elderly" or "masters athletes" or "veteran" or "post-menopausal" or "older" or "old" or "aged") *Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI Timespan=All years*
# 1	32,723	**TOPIC:** ("strength training" or "resistance exercise" or "eccentric exercise" or "lengthening contractions" or "resistance training" or "weight training" or "weight lifting" or "isometric exercise") *Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI Timespan=All years*

MedLine (Ovid MEDLINE(R) and In-Process & Other Non-Indexed Citations 1946 to February 03, 2021)

# ▲	Searches	Results
1	exp Resistance Training/ or exp Weight Lifting/	13310
2	("strength training" or "resistance exercise" or "eccentric exercise" or "lengthening contractions").mp. [mp=title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	12525
3	1 or 2	20887
4	exp "Aged, 80 and over"/ or exp Aged/	3196218
5	("older adults" or "elderly" or "masters athletes" or "veteran" or "post-menopausal" or "older" or "old").mp. [mp=title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	1659958
6	4 or 5	4336082
7	3 and 6	5350
8	("muscle dysfunction" or "exercise induced muscle damage" or "muscle damage" or "muscle soreness" or "exercise recovery" or "fatigue" or "recovery" or "creatine kinase" or "myoglobin" or "responses" or "Doms").mp. [mp=title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	1567210
9	7 and 8	1087

EMBASE (Embase 1974 to 2021 February 03)

Searches	Results	Results
1	exp Resistance Training/ or exp Weight Lifting/	24272
2	("strength training" or "resistance exercise" or "eccentric exercise" or "lengthening contractions").mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword, floating subheading word, candidate term word]	16291
3	1 or 2	31597
4	exp "Aged, 80 and over"/ or exp Aged/	3098023
5	("older adults" or "elderly" or "masters athletes" or "veteran" or "post-menopausal" or "older" or "old").mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword, floating subheading word, candidate term word]	2555417
6	4 or 5	4790270
7	3 and 6	7773
8	("muscle dysfunction" or "exercise induced muscle damage" or "muscle damage" or "muscle soreness" or "exercise recovery" or "fatigue" or "recovery" or "creatine kinase" or "myoglobin" or "responses" or "Doms").mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword, floating subheading word, candidate term word]	2102466
9	7 and 8	1411

Scopus

ID	Query	Documents
result #4	(TITLE-ABS-KEY ("strength training" OR "resistance exercise" OR "eccentric exercise" OR "lengthening contractions" OR "weight training" OR "resistance training" OR "weight lifting")) AND (TITLE-ABS-KEY ("muscle dysfunction" OR "muscle damage" OR "muscle soreness" OR "exercise recovery" OR "fatigue" OR "recovery" OR "creatine kinase" OR "myoglobin" OR "Doms" OR "responses" OR "exercise induced muscle damage")) AND (TITLE-ABS-KEY ("older adults" OR "elderly" OR "veterans" OR "masters athletes" OR "post-menopausal" OR "older" OR "old" OR "aged"))	3,543
result #3	TITLE-ABS-KEY ("older adults" OR "elderly" OR "veterans" OR "masters athletes" OR "post-menopausal" OR "older" OR "old" OR "aged")	7,053,782
result #2	TITLE-ABS-KEY ("muscle dysfunction" OR "muscle damage" OR "muscle soreness" OR "exercise recovery" OR "fatigue" OR "recovery" OR "creatine kinase" OR "myoglobin" OR "Doms" OR "responses" OR "exercise induced muscle damage")	7,436,436
result #1	TITLE-ABS-KEY ("strength training" OR "resistance exercise" OR "eccentric exercise" OR "lengthening contractions" OR "weight training" OR "resistance training" OR "weight lifting")	37,021

SportDiscus

Search ID#	Search Terms	Search Options	Actions	
S4	S1 AND S2 AND S3		**Expanders** - Apply equivalent subjects **Search modes** - Boolean/Phrase	View Results (605) View Details Edit
S3	("muscle dysfunction" or "exercise induced muscle damage" or "muscle damage" or "muscle soreness" or "exercise recovery" or "fatigue" or "recovery" or "creatine kinase" or "myoglobin" or "Doms" or "responses")		**Limiters** - Language: English **Expanders** - Apply equivalent subjects **Search modes** - Boolean/Phrase	View Results (78,981) View Details Edit
S2	("older adults" or "elderly" or "masters athletes" or "veteran" or "post-menopausal" or "older" or "old" or "aged")		**Limiters** - Language: English **Expanders** - Apply equivalent subjects **Search modes** - Boolean/Phrase	View Results (102,134) View Details Edit
S1	("strength training" or "resistance exercise" or "eccentric exercise" or "lengthening contractions" or "resistance training" or "weight training" or "weight lifting" or "isometric exercise")		**Limiters** - Language: English **Expanders** - Apply equivalent subjects **Search modes** - Boolean/Phrase	View Results (38,865)

Appendix B: Online Survey

p. 1 Introduction

THANK YOU FOR TAKING THE TIME TO VISIT OUR SURVEY

Before you begin we would like to thank you for taking the time to complete this survey. The data collected from this survey will be used in research aiming to prevent muscle loss with with advancing age using exercise. For this reason, we are asking **only those over 70 years of age** to complete this survey.
This survey should take approximately 10-15 minutes to complete. Please do not skip questions as everything you write is useful. Answer every question to the best of your knowledge, there are no wrong answers! The questions will appear in sections, please ensure you complete all the sections. For data analysis purposes, some answer boxes are limited to just a few words.
It is up to you if you wish to participate in this survey. You can withdraw from this survey at any time simply by closing the browser web page. Unfortunately, once you have submitted your survey response, we are unable to remove anonymised data from our records. By submitting your responses to the survey you are providing your consent to participate in this questionnaire and for researchers to access your responses. All data will be anonymised before use in any publication.
At the end of the survey you will be asked if you wish to provide your contact information for future research. You are under no obligation to provide this information. If you do not wish to share this information please leave the answer boxes blank.
If you have any queries regarding the completion of this survey please contact e.j.hayes2@newcastle.ac.uk
Top of Form

p. 2 GDPR Regulations

Newcastle University will be using information from you in order to undertake this research study and will act as the data controller for this study. This means that Newcastle University is responsible for looking after your information and using it properly. When we use personally-identifiable information from people who have agreed to take part in research, we ensure that it is in the public interest. Your rights to access, change or move your information are limited, as Newcastle University needs to manage your information in specific ways in order for the research to be reliable and accurate. If you withdraw from the study, Newcastle University will keep the information about you that has already been obtained. To safeguard your rights, the minimum personally-identifiable information will be used. You can find out more about how Newcastle University uses your information at ***https://www.ncl.ac.uk/data.protection/dataprotectionpolicy/privacynotice/*** *and/or by contacting Newcastle University's Data Protection Officer (Maureen Wilkinson,* ***rec-man@ncl.ac.uk****). We will use your name and contact details (telephone number, email address) to contact you about the research study if you choose to provide this information. We will use date of birth in order to understand the demographics of our respondents. Individuals at Newcastle University may look at your research data to check the accuracy of the research study. The only individuals at Newcastle University who will have access to information that identifies you will be individuals who need to contact you if you indicated you would be interested in future research.*

If you agree to take part in the research study, information provided by you may be shared with researchers running other research studies at Newcastle University and in other organisations. Your information will only be used by organisations and researchers to conduct research.

p. 3 Age, Gender, and Physical Capability

In this section, we will gather data about your age and general physical health

1 What is your date of birth?

2 What is your gender?

Male
Female
I'd prefer not to say
Show all (4)

a If you selected Other, please specify:

3 Are you able to walk around the house and indoors?

Independent (but may use aid e.g. stick)
Walk with help of one person (physical, verbal or supervision)
Wheelchair independent
Show all (4)

4 Are you able to walk up and down the stairs?

Able unassisted
Need help (physical, verbal, carrying aid)
Unable

5 Please select an answer for each row. Are you able to...

	Independent (I can do everything myself)	I need some help from another person	I am dependent on another person to help me
...feed yourself?	Checkbox	Checkbox	Checkbox
...groom yourself (hair, teeth, shaving etc.)?	Checkbox	Checkbox	Checkbox
...dress yourself?	Checkbox	Checkbox	Checkbox
...transfer from bed to chair and back?	Checkbox	Checkbox	Checkbox
...use the toilet?	Checkbox	Checkbox	Checkbox
...bathe yourself?	Checkbox	Checkbox	Checkbox

6 In general, would you say that your physical health is...

Excellent

Very good
Good
Show all (5)

7 In general, would you say that your mental health is...

Excellent
Very good
Good
Show all (5)

p. 4 Physical Activity Status

In this section, we will gather data on your current physical activity levels

8 On average, how much time in a day do you spend doing physical activities (e.g. going for a walk, jogging, gardening, housework, DIY, sports activities, stretching)?

I do not do any physical activities
Less than 30 minutes
30 minutes to 1 hour
Show all (7)

9 On average, how much time in a day are you sedentary (e.g. sitting watching TV, reading, computer, sitting outside) excluding sleeping time?

Less than 2 hours
2 to 4 hours
4 to 6 hours
Show all (6)

10 Do you participate in any aerobic exercise (e.g. cycling, jogging, spinning classes, dancing, swimming)?

Top of Form
Yes
No

a How often do you do this exercise or a combination of different aerobic exercises?

Once per week
Twice per week
Three to four times per week
Show all (6)

i On average, what intensity is this exercise?

Very light (e.g. stretching)
Light (e.g. slow dancing, boules)
Moderate (e.g. cycling slowly, walking continuously)
Show all (5)

Resistance training activities are defined as 'any physical activity which produces a muscle contraction against an external force'. This type of exercise includes weight lifting, resistance bands, body weight squats, the use of dumbbells, and any other similar activity.

11 Do you currently participate in resistance training activities (e.g. weight lifting, body-weight exercises, resistance band exercises)?

Yes
No

a How often do you do this exercise or a combination of different resistance training exercises?

Once per week
Twice per week
Three to four times per week
Show all (6)

p. 5 Barriers and Motivators for Resistance Training Participation

In this section, we will gather data on your barriers and motivations for participating in resistance training activities.

12 What are the motivators that may encourage you to participate in resistance training activities (e.g. weight lifting, body-weight exercises, resistance band exercises)?

13 What are the barriers that may prevent you from participating in resistance training (e.g. weight lifting, body-weight exercises, resistance band exercises)?

14 If you have recently started resistance training, what encouraged you to do so?

15 If you have performed resistance training in the past but no longer do so, what were your reasons for stopping?

16 Assuming you have been given the appropriate equipment and instructions, in what environment would you feel most comfortable performing resistance training?

Local gym
Community centre
Outdoor space
Show all (5)

a If you selected Other, please specify:

p. 6 Knowledge of Exercise Recovery

Roy has recently begun lifting weights in his local gym to try and improve his leg strength after having a fall. During his last session he decided to challenge himself and lifted heavier weights than usual. Once he had finished his session he drank a glass of milk and made his way home. The next day, Roy experienced soreness in his legs when he stood up from his chair or walked up stairs. This pain got worse over the next day, and then slowly began to subside. Once the pain had gone, Roy felt happy to go to the gym again.

17 Would you expect Roy's muscles to be sore in the days following resistance training?

Yes
No

This next session is designed to help us understand what older adults already know about exercise recovery. Please do not skip questions if you do not know the answer, as discovering what is not known is just as important to us.

18 Have you ever heard of the term 'post-exercise muscle damage'?

Yes
No

19 If yes, in your own words, can you describe what you understand by the term 'post-exercise muscle damage'?

20 Have you ever heard the term 'delayed-onset muscle soreness' (DOMS)?

Yes
No

21 If yes, in your own words, can you describe what you understand by the term 'delayed-onset muscle soreness' (DOMS)?

Muscle soreness can occur as a result of exercise your body finds challenging. It is often described as an aching or burning in the muscles in the hours or days following exercise. For example, Roy experienced pain in his leg muscles when walking up the stairs the day after performing lower body weights.

22 If you were experiencing delayed-onset muscle soreness (DOMS), do you think this would discourage you from completing your usual daily activities (e.g. gardening, cleaning, walking)?

Yes
No
To some extent

23 If you were experiencing delayed-onset muscle soreness (DOMS), do you think this would discourage you from participating in further exercise until the pain had subsided?

Yes

No
To some extent

p. 7 Attitudes Towards Recovery Interventions

After Roy had been lifting weights in the gym he drank a glass of cold milk to rehydrate. This is because he has heard that milk has proteins and other nutrients that may help his muscles to recover quicker and prevent muscle soreness.

24 You may have experienced muscle soreness in the past after heavy gardening or DIY, jogging or exercising in a gym. If so, what did you do to ease muscle soreness and improve exercise recovery?

25 What other recovery strategies can you describe that might reduce muscle soreness that you have not personally used?

26 This question focuses on exercise recovery supplements specifically. An exercise recovery supplement is specially designed to promote exercise recovery and often comes in the form of food, drink, powders or tablets. Have you ever purchased an exercise recovery supplement for yourself?

Yes
No

a What supplement(s) did you purchase?

b What are your views on exercise recovery supplements for older adults?

c Another strategy to aid exercise recovery and reduce muscle soreness is the consumption of certain whole foods. This can include, but is not limited to; berries, fruit, meat, milk, and fish. Are these options more or less acceptable to you than supplements as an exercise recovery intervention?

More acceptable
Less acceptable
The same

i What is your reason for this?

ii Were you aware that these types of food could improve exercise recovery?

Yes
No

d We are specifically interested in milk as an exercise recovery beverage in older adults. Would this be an acceptable strategy to you?

Yes
No

Maybe

i Please explain your answer?

e Research suggests that drinking 500 mL (approximately one pint) of milk after exercise could be effective for improving exercise recovery. Do you think you could drink this volume (500 mL) of milk?

Yes
No

i Would you be willing to drink this volume (500 mL) of milk after exercise?

Yes
No

p. 8 Future Research

27 Would you be willing to be contacted by our research group to participate in future research?

Yes
No

28 If you are willing to be contacted, how would you prefer to be contacted?
Telephone
Email
Post

If you are willing to be contacted, please provide your preferred contact information below. You do not have to provide this information if you do not wish to be contacted.

29 Full Name

30 Phone number

31 Email address

32 Postal address

p. 9 Survey Feedback

33 Please provide any feedback you have for this survey

p. 10 Final page

Thank you for completing this survey! Your responses will help us to understand older adults' perceptions of muscle damage and exercise recovery. We hope to use this information to inform future recommendations for exercise and recovery strategies that may prevent muscle loss in older age.
If you have any queries regarding this research please email e.j.hayes2@newcastle.ac.uk
Thank you again!

Appendix C: Exit Survey

p. 1 Page 1

Before you begin we would like to thank you for taking the time to complete this survey. The data collected from this survey will be used in research aiming to prevent muscle loss with advancing age using exercise.
This survey should take approximately 10-15 minutes to complete. Your personal information will not be used for research purposes. Please do not skip questions as everything you write is valuable. Answer every question to the best of your knowledge, there are no wrong answers! The questions will appear in sections, please ensure you complete all the sections. For data analysis purposes, some answer boxes are limited to just a few words.
It is up to you if you wish to participate in this survey. You can withdraw from this survey at any time simply by closing the browser web page. Unfortunately, once you have submitted your survey response, we are unable to remove anonymised data from our records. By submitting your responses, you are providing your consent to participate in this survey and for researchers to access your responses. All data will be anonymised before use in any publication.
At the end of the survey you will be asked if you wish to provide your contact information for future research. You are under no obligation to provide this information. If you do not wish to share this information please leave the answer boxes blank.
If you have any queries regarding the completion of this survey please contact Ellie Hayes at e.j.hayes2@newcastle.ac.uk
Thank you!

p. 2 Participant Information

1 Participant ID:

2 Date of Birth:

3 Sex:

Top of Form
Male
Female
I'd prefer not to say

4 Study Supplement:

Skimmed milk
Whole milk
Juice

p. 3 Attitudes and Barriers to Milk Consumption

5 Please describe your general experience of consuming the supplement provided to you during this study?

a Would you say your general experience of consuming the supplement was...

Positive
Neutral
Negative

6 Please comment on your thoughts surrounding the volume (2 x 500 ml) of liquid you were asked to drink during this study?

7 Please comment on your thoughts surrounding the taste of the liquid you were asked to drink during this study?

Top of Form

8 Did you experience any gastrointestinal issues as a result of consuming your supplement during the course of the study?

Yes
No

9 Would you be willing to consume your supplement regularly after resistance exercise in the future?

Yes
No
Maybe

a Please explain your answer?

10 Did you experience any changes to your habitual diet as a result of consuming the supplement given to you during this study? Top of Form

11 Do you think consuming 2 x 500 ml of your given supplement regularly is feasible?

Yes
No
Maybe

a Please explain your answer?

p. 4 Knowledge of Recovery Supplements

12 Before participating in this study, were you aware that milk may have the potential to improve exercise recovery?

Yes
No
Add item
Add item

13 What other recovery strategies are you aware of?

14 What are your views on exercise recovery supplements for older adults?

15 Are any of these more acceptable than milk as a recovery strategy? Tick all that apply.

Meat
Fish
Yoghurt
Show all (8)

p. 5 Experience of Exercise Induced Muscle Damage

16 You may have experienced muscle soreness during this study, if so, do you think it affected your habitual daily activities (e.g. going for your usual walk, doing housework etc.)?

Yes
No

a Please explain your answer?

b If you were experiencing muscle soreness outside of the constraints of the study, do you think you would be discouraged from participating in further exercise until the pain had subsided?

Yes
No
To some extent

i Please explain your answer?

p. 6 GDPR Regulations

Newcastle University will be using information from you in order to undertake this research study and will act as the data controller for this study. This means that Newcastle University is responsible for looking after your information and using it properly. When we use personally-identifiable information from people who have agreed to take part in research, we ensure that it is in the public interest. Your rights to access, change or move your information are limited, as Newcastle University needs to manage your information in specific ways in order for the research to be reliable and accurate. If you withdraw from the study, Newcastle University will keep the information about you that has already been obtained. To safeguard your rights, the minimum personally-identifiable information will be used. You can find out more about how Newcastle University uses your information at ***https://www.ncl.ac.uk/data.protection/dataprotectionpolicy/privacynotice/*** *and/or by contacting Newcastle University's Data Protection Officer (Maureen Wilkinson,* ***rec-man@ncl.ac.uk****). We will use your name and contact details (telephone number, email address) to contact you about the research study if you choose to provide this information. We will use date of birth in order to understand the demographics of our respondents. Individuals at Newcastle University may look at your research data to check the accuracy of the research study. The only individuals at Newcastle University who will have access to information that identifies you will be individuals who need to contact you if you indicated you would be interested in future research.*

If you agree to take part in the research study, information provided by you may be shared with researchers running other research studies at Newcastle University and in other organisations. Your information will only be used by organisations and researchers to conduct research.

p. 7 Final page

Thank you for completing this survey! Your responses will help us to understand older adults' perceptions of milk for exercise recovery. We hope to use this information to inform future recommendations for exercise and recovery strategies that may prevent muscle loss in older age.
If you have any queries regarding this research please email Ellie Hayes at e.j.hayes2@newcastle.ac.uk
Thank you again!