Exploration Of the Use of Sensor Data for Diagnosis and Monitoring of Osteoarthritis in Companion Animals

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Abstract

Canine osteoarthritis is a chronic disease, diagnosed in 80% of dogs aged eight and over. Despite the health and welfare concerns posed by the condition, osteoarthritis often remains undiagnosed until unrelated veterinary appointments, delaying treatment, while straining the vet-owner relationship. When considering possible solutions to delayed diagnosis, human medicine demonstrates the potential for accelerometers to detect gait impairing conditions. While similar methods may be applicable to veterinary healthcare, their use would first require the identification of condition specific abnormalities in measurable gait parameters. This thesis explored potential associations between osteoarthritis, activity counts, and step count (Chapters 2 and 4), before assessing the transferral of automated methods of step detection between companion animal species (Chapter 5). Finally, the thesis established methods for deploying sensor technology in veterinary therapeutics, to address the unmet needs of vets and owners (Chapter 3). The detailed experiments highlighted associations between mean activity counts, osteoarthritis, and age, before exploratory analysis suggested correlations between the initial step count, age and osteoarthritis severity. Due to the capacity for mean activity counts to distinguish between sound and arthritic individuals, the measurement of this parameter may support the diagnosis of osteoarthritis. For the filtered step count, the effects of condition severity could not be isolated from those associated with age, perhaps limiting the use of this parameter to condition monitoring. Despite this, observations were based on a small cohort, and must be considered cautiously. The Delphi Consultation process then identified pitfalls in the pathway to diagnosis, before describing potential applications for sensor technology to overcome these. A final study highlighted the accuracy of a defined canine pedometer algorithm when applied to feline data, before identifying areas for refinement. The studies highlight potential applications of sensor technology in the monitoring of canine osteoarthritis, while addressing pitfalls in the pathway to effective diagnosis.

Dedication

For Ann Isabella McIntyre. I did it, Nana!

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Jack O'Sullivan kindly provided the accelerometer dataset used throughout chapter 2, before streamlining the code, which was applied to chapters 2, 4 and 5. Jack also supported the creation of the discussion board implemented in Chapter 3. Next, Ed Gomersall collected play data from sound dogs, which was subsequently used throughout Chapter 4, and Celeste Leal supported the collection of activity data from cats.

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Chapter 1. Introduction and Literature Review

Canine Osteoarthritis (OA) is a degenerative disease, characterised by a loss of cartilage in synovial joints (Bland 2015). Occurring both secondary to injury and idiopathically, there are a multitude of predisposing factors including age, breed and body weight (Mele 2007). Progression of OA ultimately results in friction between bones, causing inflammation, joint misuse and chronic pain (Bland 2015). When considering the chronic pain associated with OA, it would be reasonable to regard this disease as an imposition on the five freedoms (a useful baseline for welfare assessment), most notably freedom from pain and discomfort (Farm Animal Welfare Council 1993), allowing OA to be viewed as concern from both a health and welfare perspective. The clear welfare implications associated with OA become particularly troubling when considering the estimated prevalence of this condition affecting approximately 80% of those over the age of eight (Anderson et al 2018).

Despite the major health and welfare concern posed by OA, this disease is frequently undiagnosed until attendance at an unrelated and routine veterinary appointment (Cachon et al 2018), with flaws in diagnostic methods perhaps contributing to the problem of underdiagnosis (Belshaw 2017). Current diagnostic methods (e.g. The Canine Osteoarthritis Staging Tool - COAST) are subjective and reliant upon the perceived condition of the individual from the perspective of the owner and veterinarian (Cachon et al 2018). As scoring methods describe the observed condition of the animal at a 'snapshot' in time and the individual's behaviour can be influenced by environment, it would be fair to consider these methods are neither accurate nor reliable. In addition to problematic diagnostic methods, the issue of under diagnosis could also be attributed to the need for an owner to first recognise indicators of the disease, before establishing that an appointment is required. As numerous early indicators of OA, including behavioural changes and inactivity stiffness (Pettitt and German 2015) can be subtle and intermittent (Belshaw 2017), it becomes reasonable to consider that these could be overlooked, preventing diagnosis until later stages of the disease (Mathews et al 2014).

Although 50% of OA cases are diagnosed in individuals between the ages of 8 and 13 (Mele 2007), this condition often arises secondary to events including injury and developmental joint conditions in young dogs (Trostel et al 2002). As developmental conditions can predispose young dogs to OA, while half of all diagnoses involve elderly individuals, it is probable that a substantial canine population could be living with undetected OA for many years before a formal diagnosis is made (Cachon et al 2018).

Following a diagnosis of OA, changes to the length and frequency of exercise can be a key feature of symptom management (Bound et al 2011), an intervention which can have significant impacts on both dog and owner. While many dog walks are motivated by the animal's need for exercise, common outcomes of this activity, as noted by owners, include the health benefits of improved wellbeing and increased physical activity (Westgarth et al 2017). When reducing the length and duration of walking exercise, the health benefits associated with dog ownership are constrained, with many owners experiencing a reluctance to exercise in the absence of their dog due to guilt (Belshaw et al 2020).

Although a diagnosis of OA has implications for both owner and dog, early diagnosis and intervention could prevent or delay the long-term decline in a dog's quality of life (Cachon et al 2018), while perhaps reducing the negative emotional and physical effects experienced by the owner. As an early diagnosis could greatly improve the welfare of the dog, while negating potential strain on the dog-owner relationship, methods for detecting the early indicators of OA become increasingly necessary.

When considering possible solutions to the problem of OA underdiagnosis, human medicine demonstrates the diagnostic potential of gait analysis and sensor technology.

Gait analysis is a useful tool for diagnosing and monitoring human gait impairing conditions, including Parkinson's disease and osteoarthritis. Although the traditionally used motion capture technology is restricted to use in controlled settings, sensor technology such as accelerometers could offer measurements of spatio-temporal gait parameters, within real-world surroundings (Sun et al 2017).

The use of sensor technology in human gait analysis has successfully highlighted disease-specific changes in gait parameters, such as shuffling in Parkinson's Disease (Schlachetzki et al 2017), and gait speed of multiple sclerosis patients (Severini et al 2017). As the early stages of OA also cause subtle changes in gait, it is possible the technology and parameters studied in human medicine could be transferrable to canine gait studies, potentially offering a solution to the problem of OA underdiagnosis.

This literature review will compare the spatio-temporal gait parameters measured in human and canine gait analysis, identifying the technology most commonly used, and will present the potential for interchangeability of parameters and technology between human and canine studies.

1.1 Human gait studies

Current diagnostic methods for human gait impairing conditions can involve the use of observation and scoring tools, such as the Western Ontario and McMaster Universities (WOMAC) osteoarthritis index. As with the COAST tool used in veterinary medicine, the WOMAC score relies on clinician observations, as well as a patient's own interpretation of their condition (Barrois et al 2015). Although scoring tools are a validated method of diagnosis and monitoring, their subjective nature could become problematic when considering the unique weighting of impacts among individuals and clinicians, and the potential effects of this on overall consistency across all cases.

In terms of accurate and consistent methods for measuring features of human gait, motion capture technology is often regarded as a gold standard, however the associated need for a specialized laboratory setting makes alternative methods attractive (Schlachetzki et al 2017). Sensor technology, including accelerometers, offers an alternative for use in real-world settings, which could be validated against motion capture technology.

To identify parameters frequently recorded in human gait studies and the technology used for doing so, the Google Scholar search engine and Scopus database were used to search key terms and phases, including but not restricted to: 'human gait', and 'gait analysis protocol'.

References were then filtered and identified for review by considering factors including number of citations, with a minimum of five for consideration. Such a threshold was established to ensure the relevance of the selected literature, while limiting the extent to which references would be excluded due to recent publication dates. Additional considerations were paid to the nature of condition investigated (if possible), whereby a range of conditions, including mechanical and neurological, were sought. A final consideration was the provision of parameter definitions, whereby failure to define parameters led to the rejection of that study.

By reviewing literature in the described method, 16 gait parameters were identified as frequently recorded in human gait studies (see Table 1.1). While it is acknowledged that a brief sample of five studies referenced in Table 1.1 cannot be representative of the entire literature, it is still possible to notice differences in measured parameters, as well as technology used. Furthermore, based on citations, it would be reasonable to consider the identified studies as key references.

Table 1.1. Parameters measured in human gait studies, including example references.

	Human Studies – Measured Parameters				
	Reference				
	Schlachetzki et al (2017)	Sun et al (2017)	Watanabe et al (2011)	Zago et al (2018)	Tadano et al (2016)
Technology					
Motion Capture		✓	✓	✓	
High speed camera		✓			
Inertial sensors	✓	✓	✓	✓	✓
Parameter					
Walking speed					
Stride length	✓	✓	✓	✓	
Cadence	✓	✓		✓	
Gait cycle		✓			✓
Velocity	✓	✓		✓	
Stride duration	✓			✓	
Stride count				✓	
Stride Velocity			✓		
Step duration				✓	
Step count		✓			
Step length		✓		✓	✓
Stance/Swing/Double support durations	✓			✓	✓
Lower limb joint angles			✓	✓	✓
Heel strike and toe off angles	✓				
Foot clearance	✓				
Gait variation	✓				

Of the 16 human gait parameters included in Table 1.1, stride length is measured in a majority of four referenced studies, suggesting this parameter may be a key feature of human gait evaluation, in which changes could be indicative of underlying conditions. While lower limb joint angles were also frequently measured, featuring in three cited studies, two of these involve the use of motion capture technology and inertial sensors (Watanabe et al 2011 and Zago et al 2018). As motion capture is considered gold standard for gait analysis, it is possible that lower limb joint angles were measured to assist protocol validation. The potential use of joint angles in protocol validation suggests that while these parameters are frequently measured in the cited studies, their purpose may not lie solely with the identification of gait abnormalities. When considering the remaining parameters, a total of seven including walking speed and stride velocity are each measured in just one study, suggesting these parameters may not be fundamental for achieving a baseline gait evaluation. Alternatively, as approximately half of the underrepresented parameters are measured by Zago et al (2018), one of only two sampled studies to involve a neurological condition (Parkinson's Disease), it becomes reasonable to consider that abnormalities in these parameters could be disease-specific, perhaps justifying why these were not measured elsewhere in the sampled studies.

Study design can influence the potential for identifying abnormalities in the recorded parameters. By comparing features of the referenced human studies, including sample size and methods, advantages and limitations of study design can be identified.

In terms of sample size, Schachetzki et al (2017) set a good example, recruiting a cohort of 63 participants diagnosed with Parkinson's disease. The study also included 101 healthy age matched controls. By sampling large cohorts, a more representative view of the target population can be achieved, while the use of age matched controls could reduce variability in gait measurements used for reference. In contrast, Watanabe et al (2011) used a sample size of just three individuals, with no control group. Use of such a low sample size could impact the potential for detecting gait abnormalities when compared to large cohort studies.

The potential for detecting gait abnormalities could also be improved by incorporating repeat measures. The use of repeat measures can be seen when revisiting the example of Schachetzki et al (2017), a longitudinal study including three instances of data collection, during which measurements were repeated four times. By including repeat measurements across a duration of time, the likelihood of detecting gait abnormalities and disease progression is increased. Contrastingly, Tadano et al included just one round of data collection, whereby participants were noted to complete a single 7m walk within 10-30 seconds. By failing to include repeat measurements, the duration for data recording is severely restricted, limiting the potential of identifying gait abnormalities.

To briefly summarise the human gait studies, of the 16 gait parameters identified, foot clearance, as well as heel strike and toe off angles have the most potential for use in canine studies, owing to the possibility that these parameters could highlight lameness, a common indicator of OA. Of the remaining parameters in Table 1.1, stride length and lower limb joint angles will be taken forward for comparison with canine studies. The specified parameters have been selected as their prioritisation in human studies is not matched in the canine references, allowing for contrast between the most and least prioritised.

In the following section, the gait parameters prioritised for measurement in the human and canine studies will be compared.

1.1.1 Parameter comparison

Differences between human and canine studies are apparent when considering the number and type of spatio-temporal gait parameters measured. From reviewing literature using the methods described for the human references, 20 gait parameters were identified as frequently recorded in canine gait studies (see Table 1.2). While the five studies reviewed are not expected to be representative of the entire literature, they could be regarded key references, based on selection criteria.

Table 1.2. Parameters measured in canine gait studies, including example references

	Canine Studies – Measured Parameters				
	Reference				
	Hayati et al (2019)	Jenkins et al (2018)	Rhodin et al (2017)	Maes et al (2008)	Surer et al (2020)
Technology					
Motion Capture					✓
High speed camera	✓	✓		✓	
Inertial sensors	✓	✓	✓		
Force platform					✓
Parameter					
Walking speed					✓
Stride length				✓	✓
Cadence					✓
Gait cycle duration				✓	
Stride duration					✓
Stride count	✓	✓			✓
Stride frequency	✓				
Step duration					✓
Step count		✓			
Step length					✓
Step frequency	✓				
Stride/Stance/Swing durations		✓			
Footfall timing	✓			✓	
Dorso-ventral/antero-posterior accelerations	✓				
Maximum/minimum head difference			✓		
Maximum/minimum pelvic difference			✓		
Gait cycle frequency				✓	
Duty factor				✓	
Joint kinematics					✓
Vertical ground reaction forces					✓

The measurement of stride length and lower limb joint angles appear to be key parameters for measuring human gait, however these parameters are each measured in just one canine reference, whereby joint angles are noted as ‘joint kinematics’. Conversely, the most popular parameter measured in canine studies is stride count, included three sampled studies, while this parameter was recorded in one human study. Although the two most common measurements in the sampled human and canine literature involve the stride, different aspects of this feature are prioritised by each study type, suggesting that some parameters could have a species-specific value to gait analysis, perhaps accounting for their varying prioritisation in human or canine investigations.

Additional comparisons can be drawn between human and canine gait studies when considering the range of parameters measured in each study type. Of the referenced human investigations, a total of 16 gait parameters were measured, while a total of 20 parameters were recorded in the canine studies. Although a broad range of joint angle measurements were recorded in the sampled human and canine literature, the terms 'lower limb joint angles' and 'joint kinematics' encompass these measurements respectively.

The difference in range of parameters measured between the sampled human and canine studies may be related to anatomy. As the number of load bearing limbs is doubled when comparing canines to humans, it would be reasonable to consider that the number of measurable gait parameters could be increased as a result. Additionally, as canines have an uneven weight distribution, identification of gait abnormalities may require the use of parameters specific to front or hind limbs, once more potentially increasing the range of variables available for measurement in canine gait studies when compared to those used in the human literature.

Differences in breeds included in the canine studies could also account for the increased range of gait parameters. While canines typically alternate between four common gaits, a further four gaits are available in their repertoire, with the preferred gait often specific to breed (Carr and Dycus 2016). As three of the sampled canine studies are each tailored to a different dog breed (Surer et al, Hayati et al and Maes et al), while the measured parameters may be specific to the breed's preferred gait, the use of a broad range of parameters across all sampled canine studies could be considered justified. As human gait analysis encompasses just five gaits common to all humans (depending on physical condition), it becomes fair to consider that a reduced range of gait parameters may be required when compared to canine gait studies.

A further cause for the range of gait parameters used in canine studies could involve increased scope for compensatory mechanisms in dogs, whereby gait forces can be redistributed to healthy limbs in order to compensate for lameness (Sharkey 2013). As misinterpretation of compensatory mechanisms could lead to misdiagnosis, an increased range of parameters may be measured in canine gait studies to establish healthy baselines.

Use of a healthy baseline can allow for discrimination between abnormalities characteristic of gait impairing conditions and those arising from compensatory mechanisms.

To briefly summarise the comparison between human and canine gait studies, stride count is the most frequently measured of all 20 canine gait parameters included in Table 1.2, with inclusion in 3 referenced studies, suggesting this is a key parameter for measurement when evaluating canine gait. The second most measured parameters in the referenced canine studies include stride length and football timing. Although footfall timing is not recorded in Table 1.1, stride length is the most measured parameter in the referenced human studies, indicating that measurement of this parameter could be key to both human and canine gait studies.

1.1.2 Definition comparison

When comparing human and canine gait studies, variation can be found in the definitions of key parameters. As the measurement of parameters ultimately depends on how these are defined, clear definitions are required to reduce ambiguity, and ensure reproducibility. Definitions of key parameters highlighted in the human and canine studies have been extracted (see Table 1.3&1.4)

Table 1.3 Definitions of parameters used in referenced examples of human studies

	Human Studies – Parameter Definitions				
	Reference				
	Schlachetzki et al (2017)	Sun et al (2017)	Watanabe et al (2011)	Zago et al (2018)	Tadano et al (2016)
Parameter					
Walking speed		-	-	-	-
Stride length	(m) Distance between two sequential points of midstance contacts with the same foot	(m) No further definition	(cm) Estimated using forward acceleration of the foot	(m) Distance between two consecutive heel strikes of the same foot	-
Cadence	(Steps/min) Step rate per minute	(steps/min) Inverse of time between adjacent initial contacts	-	(steps/min) Number of steps per minute	-
Gait cycle	-	(s) Time between initial contacts of same foot	-	-	(s) Duration of a gait cycle
Velocity	(m/s) Walking speed in a designated direction	(m/s) Gait cycle/stride length	-	(m/s) Ratio between walking distance and duration	-
Stride duration	(s) Duration of one gait cycle	-	-	(s) Time between two consecutive initial contacts of the same foot	-

	Human Studies – Parameter Definitions				
	Reference				
	Schlachetzki et al (2017)	Sun et al (2017)	Watanabe et al (2011)	Zago et al (2018)	Tadano et al (2016)
Parameter					
Stride count	-	-	-	Number of strides per minute	-
Stride velocity	-	-	(m/s) Estimated using stride length and time	-	-
Step duration	-	-	-	(%) Time between initial contact of one foot and the contralateral initial contact, computed as percentage of the stride duration	-
Step count	-	Number of steps in one 16m lap	-	-	-
Step length	-	(m) Distance between heel location during foot ground contact	-	(m) Estimation based on vertical pelvis displacement and leg length	(cm) Distance between a heel-strike (or toe-off) of both feet
Stance duration	(%) Period in gait when the foot is in contact with the floor	-	-	(%) Time from the initial contact to the toe off for the same foot	-

	Human Studies – Parameter Definitions				
	Reference				
	Schlachetzki et al (2017)	Sun et al (2017)	Watanabe et al (2011)	Zago et al (2018)	Tadano et al (2016)
Parameter					
Swing duration	(%) Period in gait cycle when the foot is not in contact with the floor	-	-	(%) Time from the toe off of one foot to the initial contact of the same foot	-
Double support duration	-	-	-	(%) Phase in which both feet touch the ground	-
Support ratio	-	-	-	-	(%) Duration of a gait cycle in which the foot is on the ground
Lower limb joint angles		(°) Angles of hips, knees and ankles	(°) Integral of difference between angular velocities between gyroscopes	(°) Pelvic tilt angle	(°) Hip, knee and ankle joint angles, including acceleration vector of knee joint and vector at heel contact
Heel strike and toe off angles	(°) Angle between foot and ground in the sagittal plane at heel-strike/toe-off				
Foot clearance	(cm) Maximum toe height during swing phase				

	Human Studies – Parameter Definitions				
	Reference				
	Schlachetzki et al (2017)	Sun et al (2017)	Watanabe et al (2011)	Zago et al (2018)	Tadano et al (2016)
Parameter					
Gait variation	Magnitude of alterations in individual gait parameters during walking, also defined by the CV: ratio of standard deviation to the mean)				

Table 1.4. Definitions of parameters used in referenced examples of canine studies

	Canine Studies – Parameter Definitions				
	Reference				
	Havati et al (2019)	Jenkins et al (2018)	Rhodin et al (2017)	Maes et al (2008)	Surer et al (2020)
Parameter					
Walking speed	-	-	-	-	(m/s)
Stride length	-	-	-	(m) Distance between two successive footprints for the same foot	(m) Distances traversed by the markers attached on the dorsum of the forelimb paw between corresponding intervals of time
Cadence	-	-	-	-	(steps/min)
Gait cycle duration	-	-	-	(s) Time between two consecutive footfalls for the specific foot	-
Stride duration	-	-	-	-	(s) Time interval between two successive initial contacts of the same paw
Stride count	Number of strides. Time difference between two consecutive negative peaks is one stride	Number of consecutive strides within 60 seconds	-	-	-

	Canine Studies – Parameter Definitions				
	Reference				
	Havati et al (2019)	Jenkins et al (2018)	Rhodin et al (2017)	Maes et al (2008)	Surer et al (2020)
Parameter					
Stride frequency	(Hz) Established by applying fast fourier transform on dorsal-ventral accelerations	-	-	-	-
Step duration	-	-	-	-	(s) Time between final contact and initial contact
Step count	-	Number of steps in 60 seconds	-	-	Number of steps (one calculated from final contact to initial contact)
Step length	-	-	-	-	(m) Distances traversed by the markers attached on the dorsum of the forelimb paw between corresponding intervals of time
Step frequency	(Hz) Established by applying fast fourier transform on dorsal-ventral accelerations	-	-	-	-

	Canine Studies – Parameter Definitions				
	Reference				
	Havati et al (2019)	Jenkins et al (2018)	Rhodin et al (2017)	Maes et al (2008)	Surer et al (2020)
Parameter					
-Stride phase	-	The complete movement through swing and stance phase	-	-	-
Stance phase	-	(s) Time the paw is on the ground.	-	(s) Duration of contact for a limb	-
Swing phase	-	(s) Time the paw is in the air	-	(s) Duration of limb flight	-
Footfall timing	(ms) No further definition	-	-	(s) Time when paw contacts the ground, and time when last toe leaves the ground	-
Dorso-ventral/antero-posterior accelerations	(g) No further definition	-	-	-	-
Maximum/minimum head difference	-	-	Difference in displacement between two lowest and two highest values of the head per stride	-	-

	Canine Studies – Parameter Definitions				
	Reference				
	Havati et al (2019)	Jenkins et al (2018)	Rhodin et al (2017)	Maes et al (2008)	Surer et al (2020)
Parameter					
Maximum/minimum pelvic difference	-	-	Difference in displacement between two lowest and two highest values of the pelvis per stride	-	-
Gait cycle frequency	-	-	-	(Hz) No further definition	-
Duty Factor	-	-	-	(%) Fraction of the gait cycle for which the foot is in contact with the ground	-
Joint kinematics	-	-	-	-	(°) Joint angles for hip, stifle and tarsal joints, including range of motion
Vertical ground reaction forces	-	-	-	-	Amplitude

One single parameter can have a range of characterisations depending on the study in which it is measured (see Table 1.2). An example parameter with multiple definitions is velocity. Although the units to describe velocity are consistent between two human studies (m/s), the provided definitions are not. While Sun et al (2007) describes velocity as 'the gait cycle divided by stride length', Zago et al (2018) opt for the definition: 'ratio between walking distance and duration'. Ultimately, both definitions can be interpreted similarly, however the noted differences can highlight the need for clarity to enable reproducibility.

Canine studies also offer different definitions for the same measurement (comparing Table 1.2 and Table 1.3). In the human study, Zago et al (2018) describes step duration as ‘Time between initial contact of one foot and the contralateral initial contact, computed as percentage (%) of the stride duration’, indicating that the measurement of one step depends on the observation of both feet. In contrast, the same parameter recorded in a canine study is defined by Surer et al (2020) as: ‘final contact to initial contact for each thoracic limb’, recorded in seconds (s), suggesting that measurement of one step requires the observation of just the single limb in motion. As the criteria of a parameter can alter depending on the associated definitions and units, as highlighted in the ‘step duration’ example, the need for clarity when considering the potential for interchangeability of parameters between human and canine studies is emphasised.

1.2 Technology

The comparison of human and canine gait studies can highlight differences in technology used to measure parameters. While there is a range of technology available for use in gait analysis, suitability will depend on factors including study location and parameters measured.

The technology used in the human and canine gait studies has been identified (see Table 1.1&1.2), with the referenced studies favouring motion capture, inertial sensors, high speed cameras and force plate technology.

Motion capture is considered the gold standard in gait analysis technology, enabling the measurement of gait parameters via the creation of 3D models. While motion capture is often used in the validation of new gait monitoring technology, high speed cameras can also fulfil this purpose, while not being restricted to controlled environments. The portable nature of high-speed cameras is particularly useful for the validation of measurements made by inertial sensors, which are small wearable devices capable of measuring accelerations and velocity. In contrast to inertial sensors, force plates are often restricted to use in a controlled environment, where they measure ground reaction forces produced by steps taken on or across their surface.

Of the human and canine gait studies sampled, differences can be noted in the technology used, particularly force platforms, which are included in just one cited example, a canine study. The use of force plate technology by Surer et al (2020) facilitated the design of a gait analysis protocol by highlighting characteristics of a healthy dogs’ quadruple posture.

Dogs are unable to direct clinicians to their source of pain and compensatory mechanisms could lead to a misdiagnosis (Rhodin et al 2017). Thus, the cataloguing of healthy posture and weight distribution could generate a baseline reference for comparison when investigating abnormalities, perhaps reducing the scope for misdiagnosis. As the location of pain and discomfort can be communicated in human studies, the need to detect compensatory mechanisms may be less important, perhaps suggesting why force plate technology was not used in the sampled human studies.

A further difference in technology regards the use of motion capture, which was used in most human studies, while featuring just once in the sampled canine literature, whereby high-speed cameras were favoured for validation purposes. While the cost associated with motion capture may reduce accessibility to this technology (Jenkins et al 2018), usage may be further reduced in canine studies by the need for specialist surroundings. As specialised facilities may not have the necessary space for the demonstration of all gaits, while some abnormalities are gait specific (Carr et al 2016), the reduced use of motion capture in favour of high-speed recordings could ensure that all gaits can be measured in situ, such as the greyhound racetrack used by Hayati et al (2019).

1.3 Transferable features

Although gait analysis is a validated diagnostic method in human medicine, the diagnostic potential for canine conditions is less researched. As gait analysis could offer timely solutions to chronically underdiagnosed canine conditions, including OA, it becomes reasonable to question whether features of human gait analysis could be modified and transferred for use in dogs.

Gait analysis has demonstrated diagnostic use in veterinary medicine; with frequent use in horses (Crecan and Peștean 2023) and livestock, particularly cattle (Fischer et al 2022), whereby accelerometers have the capacity to detect and monitor clinical signs of disease, such as lameness (Knight 2020). While it may be possible to transfer methods between livestock and companion quadruped species, the frequent use of dogs as models for human medicine, owing to their predisposition for shared conditions (Shearin and Ostrander 2010), suggests that the transferability of human gait studies should be explored first. By transferring features from human to canine gait analysis, a one health approach (Rock et al 2009) could be used to address the issue of underdiagnosed veterinary conditions, such as OA.

Although the transfer of features from human to canine studies has associated barriers, including differences in anatomy, behaviour and communicative ability, by acknowledging lessons learned from human studies, and modifying protocols accordingly, it may be possible to overcome these obstacles.

Useful lessons learned from human gait analysis are collated by King et al (2017), in which the origins of gait variation were investigated in a single case study. From this case study), three possible categories of gait variation were established including experimental, genuine and intentional, whereby intentional deviations were identified by combining the use of MRI and observation of participant interactions. When considering canine studies, it is unlikely that a dog would intentionally mimic lameness, instead, intentional deviations in gait may be performed to mask symptoms, or compensate for these.

When considering the design of the case study, several limitations can be identified, including sample size and lack of repeat measurements. By broadening participation from one person to a single group with a common condition, accuracy of recorded data could be increased. Furthermore, inclusion of repeats could offer a more rounded interpretation of standard gait for the participant, while potentially coinciding with condition flare-ups. In addition to the lack of repeat trials, data collection was restricted to controlled settings, while an improved protocol could integrate in-situ gait measurement.

Despite the limitations of the case study, sources of gait variation (including incorrect marker placement, genuine abnormalities and deliberate deviations) have been identified. By collating and categorising possible sources of gait variation, awareness of these deviations can be raised, allowing for recognition in future studies.

The importance of marker placement for correctly interpreting causes of gait variation is also highlighted in canine gait studies. By inducing lameness in 10 clinically sound dogs, Rhodin et al (2017) identified compensatory lameness mechanisms in the head and pelvis. While the study had limitations, including the small sample size of just 10 clinically sound dogs, the restriction of data collection to the novel surface of a treadmill, and the lack of clinically lame dogs for result validation, a previously unreported compensatory mechanism was identified.

The identification of novel lameness mechanisms could allow for the modification of marker placement, to encompass any potential variation in gait arising from such mechanisms, which could be otherwise missed.

The transfer of gait parameters between human and canine gait studies could also prevent abnormalities in canine gait from being overlooked. Schlachetzki et al (2017) describes the use of parameters including foot clearance, as well as heel strike and toe off angles, which do not feature in the sampled canine studies (Table 1.2). While the specified parameters were novel to just one sampled human study (Table 1.1), the measurement of these could highlight gait abnormalities indicative of lameness across species, including unusual contact and distance between the limb and the ground. As measurement of the specified parameters could indicate lameness across species, while the definitions (Table 1.3) are universal, it is possible that these could be easily transferred for use in canine studies.

By comparing the human and canine gait analysis literature, it was possible to identify features with the highest potential for transfer between the two study types. While the novel compensatory mechanism identified by Rhodin et al (2017) could influence the placement of markers, the parameters used by Schlachetzki et al (2017), most notably heel strike and toe off angles, hold the most potential for transfer to canine studies.

1.4 Conclusion

The comparison of human and canine gait analysis literature has highlighted potential factors which could impact the interchangeability of definitions, technology and parameters between each study type. While it is possible that features of human gait analysis could be both beneficial and transferrable to canine studies, this may be dependent on the revision of definitions, to ensure suitability for canine specific gait features.

Based on this review, the gait features with the most potential for transfer from human to canine studies include foot clearance, as well as heel strike and toe off angles. The transfer potential of these specified parameters arises from their universal definitions, as well as their ability to detect unusual contact and distances between the limb and the ground, features which could be indicative of lameness across species.

Although the transfer of some definitions, technology and parameters from human to canine gait studies may not be feasible due to differences in anatomy, behaviour and communicative ability, the lessons learned in human studies could be regarded as universal. By considering the insight derived from human investigations, it may be possible to design more effective gait analysis protocols to better identify sources of gait variation and facilitate the earlier diagnosis of conditions such as canine osteoarthritis.

Chapter 2. The Relationship Between Canine Osteoarthritis, Step Count and Activity Counts

2.1 Introduction

Osteoarthritis (OA) is the most common joint disease in dogs (Lascelles 2002), affecting approximately 80% of those over the age of eight (Anderson et al 2018) and up to 20% of individuals over the age of one (Fritsch et al 2010). Occurring both idiopathically as well as secondary to injury and conditions such as hip dysplasia, with a multitude of predisposing factors including age, breed, and body weight (Mele 2007), OA causes both pain and impaired joint function (Alam et al 2011; Anderson et al 2018), modifying the behaviour of the affected individual (Hudson et al 2004). Despite the prevalence of OA, diagnosis is frequently delayed until routine and unrelated veterinary appointments (Cachon et al 2018), with subtle symptoms and flaws in diagnostic methods contributing to the problem of delayed diagnosis (Belshaw 2017).

Methods for identifying OA within general practice settings are described by Belshaw et al (2020a), whereby a presumptive diagnosis is often made using a visual assessment of the dog's gait and ability to rise and is supported with information provided by the owner, as well as the individuals clinical history, with a physical examination contributing towards a rating of severity. Similar methods are encompassed by scoring tools, such as The Canine Osteoarthritis Staging Tool (COAST). COAST combines a clinician's visual and physical assessment alongside the owner's perspective of their pet's condition, using a clinical metrology instrument, such as the Liverpool Osteoarthritis in Dogs (LOAD) score (Cachon et al 2018). As scoring tools and clinician observations reflect the perceived condition of the animal at a 'snapshot' in time, while OA symptoms are often intermittent, it could be considered that such methods may not provide a representative summary of the individual's condition, perhaps delaying diagnosis.

In addition to imperfect diagnostic methods, the problem of late diagnosis could also be attributed to the subtle presentation of symptoms associated with the early stages of OA, including inactivity stiffness, behavioural changes, and reluctance to exercise (Pettitt and German 2015). As early indicators of OA are often sporadic and difficult to identify (Belshaw 2017), it becomes reasonable to consider that owners may overlook symptoms or even misinterpret these as an inevitable consequence of aging (Lascelles et al 2002), delaying diagnosis as well as the provision of interventional treatment and pain relief until later stages of the disease (Mathews et al 2014).

Once diagnosed, key interventions for the management of OA can include the use of anti-inflammatory and analgesic medications (Bound et al 2011; Fritsch et al 2010), the provision of which supports the expectation that OA causes pain in affected individuals. As the experience of pain and the presence of disease imposes on two of the five freedoms (Animal Welfare Act 2006), OA can be considered both a health and welfare concern, highlighting the necessity for earlier diagnosis and intervention.

Additional interventions for the management of OA include changes to the length and frequency of exercise, a factor which impacts both the affected dog and their owner. While dog walks are frequently motivated by the animal's requirement for exercise, many owners note the associated health benefits of increased physical activity and improved wellbeing (Westgarth et al 2017). When altering the frequency and duration of walking exercise due to conditions such as OA, the health benefits associated with owning a dog are constrained, with many owners experiencing a caregiver burden, as well as a reluctance to exercise in the absence of their dog (Belshaw et al 2020b).

Although both dog and owner are impacted by a diagnosis of OA, early diagnosis and intervention can delay or even prevent the long-term decline in the affected dog's quality of life (Cachon et al 2018), perhaps also reducing the negative impacts experienced by the owner. As a timely diagnosis could greatly benefit the welfare of the dog, while easing strain in the dog-owner relationship, methods for detecting the early indicators of OA become essential.

When considering potential solutions to the problem of delayed diagnosis, human medicine demonstrates methods for assessing exercise capacity, such as the six-minute walk test (6MWT). The 6MWT measures the maximum distance an individual is able to walk across a flat surface, within a six-minute duration, allowing for an objective measure of functional walking capacity (Pritchard et al 2020). Although additional walking tests are available, it is thought that the 6MWT is better tolerated by participants when considering alternatives such as the shuttle walk test (Enright 2003). While the 6MWT is typically reserved for patients with cardiac or pulmonary diseases, the test can also be used to monitor those with orthopaedic problems, including arthritis (Bohannon et al 2014). As chronic pain is thought to be a predominant cause of score variation during repeat 6MWTs among arthritis patients (King et al 2022), application of repeated 6MWTs within veterinary healthcare may offer a performance-based alternative to current methods of identifying conditions associated with chronic pain, including OA. While the 6MWT is not currently applied to the detection of OA, with research instead applying this test for the detection of pulmonary and neuromuscular conditions, it is possible that distance travelled may not be a useful outcome measure for dogs, due to their four legs and wide variation in height both within and between breeds (Swimmer et al 2018; Cerda-Gonzalez et al 2016). Application of a modified 6MWT is therefore considered, whereby the number of steps and activity count is recorded during the highest six minutes of activity per day.

To further aid the detection of gait impairing conditions, human medicine demonstrates the validated diagnostic potential of sensor technologies including accelerometers, which are small, low-cost devices used to measure acceleration along a sensitive axis, providing insight into body movement in the anterio-posterior, mediolateral and vertical planes (Godfrey et al 2008). Accelerometers have been used to study human joint kinematics since the 1990's (Fong and Chan 2010), and clinical use of such devices can assist the identification of conditions such as Parkinson's disease, whereby characteristic gait abnormalities such as short steps and shuffles are detected (Shalachetzki et al 2017).

Accelerometers have also been applied to canine studies, whereby objective measures of activity can be used to evaluate the efficacy of treatment for chronic conditions, leading to interest in the use of such devices for the monitoring of disease in companion animals (Belda et al 2018; Brown et al 2010). Such uses allow for an assessment of behaviour and activity in the individuals everyday environment (Dow et al 2009), whereby they can move and range freely. When considering the diagnostic potential of accelerometers in human medicine, it would be reasonable to question whether these could also be deployed in a diagnostic capacity within veterinary healthcare settings, to enable timely detection of gait impairing conditions including OA. To investigate an accelerometers potential for detecting OA, a condition specific abnormality of a measurable gait parameter must first be identified.

Previous application of accelerometers in canine gait analysis highlights the ability of such devices for measuring gait parameters including step count, as well as estimating distance travelled (Ladha et al 2018). By recording and comparing the step and activity counts of sound and arthritic dogs during a modified 6MWT, it may be possible to identify subtle deviations associated with OA, perhaps facilitating earlier diagnosis and symptom monitoring. The aim of this chapter was to investigate the potential association between a confirmed diagnosis of OA, activity counts, and the gait parameter 'step count'. To do this, an existing accelerometer dataset collected from sound and arthritic dogs across seven-day durations was used to implement a modified 6MWT. To apply a 6MWT to accelerometer data, the six-minutes of highest continuous activity was first identified and recorded per dog, per day. Next, the pedometer algorithm developed by Ladha et al (2018), was adjusted and translated to implementation in an open-source programme, before being applied to the predefined six-minute intervals. Step candidates were then filtered to identify irregular steps, allowing step count to be considered in three categories, initial and filtered step counts, as well as irregular steps and shuffles (consisting of difference between the initial and filtered counts). Finally, Bayesian statistics as well and linear mixed effects (LME) and ridge regression models were used to explore the relationship between the step count categories, activity counts and a confirmed diagnosis of OA.

2.2 Materials and Methods

2.2.1 Ethical Statement

All methods reported throughout this chapter were conducted following approval from Newcastle university's ethical review board AWERB Project ID No: ID 828.

2.2.2 Data

This chapter made use of an existing dataset, including the acceleration data of sound and arthritic dogs belonging to varying breeds and crossbreeds, collected by O'Sullivan (2021), using Axivity AX3 triaxial accelerometers. The collar mounted devices were worn in addition to the participating dog's regular collar, and recorded data continuously at a frequency 100Hz for a duration of seven days. While most recordings commenced at midnight (00:00:00) on the first day (with one day defined as 00:00:00 – 23:59:99), some devices implemented alternative start times, resulting 11 dogs being recorded for a lesser duration of six days, with these days being defined as 23:59:00 – 23:58:99.

Of the 72 recordings used, 43 were obtained from sound (control) dogs, and 29 from dogs with a confirmed diagnosis of OA, with additional meta data detailing the age, sex, and neuter status of each dog, as well as owner defined evaluations of their dog's mobility in the form of LOAD scores (Appendix A). Within the arthritic group, age ranged from 8-16 years, with a mean age of 10.9 years, while LOAD scores varied from 2 – 52, with a mean score of 20.2. Comparatively, the control group had a lower mean age of 6.1 years, with a range of 1.5 – 13 years, as well as a lower mean LOAD score (5.5), with a range of 0-24. While metadata was complete for most dogs, the neuter status of four dogs, and LOAD scores of two dogs were not available.

Additional data collected by O'Sullivan (2021) was used for validation purposes. The validation dataset included accelerometer recordings and supporting video footage collected from four control dogs during short, leashed walks, lasting approximately five minutes with additional metadata and details of device attachment remaining consistent with those previously described. While each dog was handled by their owner, all walks were accompanied by the same researcher, maintaining a relatively consistent walking speed for each dog. The validation dataset included two males and two females of varying breeds, and while age data were unavailable for one dog, the ages of the remaining dogs ranged from 6-9, with a mean LOAD score of 5.75 (table 2.1). Of the four dogs included in the validation dataset, only one (C002FGK) was included in the wider study.

Table 2.1. Details of dogs included in the validation dataset

Dog ID	Type	Sex	Neuter status	Age	LOAD Score
C002FGK	Control	F	Y	6	9
C005MGK	Control	M	Y	7.5	4
C008FGK	Control	F	Y	9	8
C009MGK	Control	M	Y	NA	2

2.2.3 Data Processing

The first stage of data processing involved resampling the raw accelerometer data files, using the omconvert conversion program within the OMGUI software, to ensure data were sampled evenly at a rate of 100Hz. R (R Studio Team 2020) was then used to load the resampled data, before identifying the six minutes of highest continuous activity per dog, per day, from which step count would be extracted. While the use of a six-minute duration was required to implement a modified 6MWT, the need for this to occur continuously owes to the fact that step identification relied on data recorded prior to each step candidate, meaning that step candidates could be missed, or falsely identified if non-continuous data were stitched together.

To identify the six-minutes of highest continuous activity per day, the 'activityCounts' package was first used to generate activity counts from the X, Y and Z axes of the resampled accelerometer data. Activity counts are an inference of activity intensity, often spanning one-minute durations, and are typically referenced as counts per minute (Michel and Brown 2011; Morrison et al 2013). While the use of activity counts in human studies typically focusses on the vertical axis, comparison of counts derived from the vertical and integrated axis show little variation in canine studies (Yam et al 2011). As this study required an inference of activity intensity for all three axes of movement, the next step of data processing involved generating the integrated axis, this was done by calculating the vector magnitude (VM), using the X, Y and Z axis, as demonstrated in equation 2.1.

$$VM = \sqrt{X^2 + Y^2 + Z^2} \tag{2.1}$$

An activity threshold of 1352 counts per minute within the integrated axis was then selected, below which dogs were considered to be sedentary. While this threshold was enforced by Morrison et al (2013) using Actigraph GT3X accelerometers, the same threshold was implemented in this study for data collected using Axivity devices. Next, for each recorded day, active periods with a minimum duration of six minutes were identified, before applying a rolling mean and selecting the six-minute window with the highest mean activity count, from which step count would later be obtained. Upon selecting the six-minute windows, the corresponding mean activity counts were recorded per dog per day. If activity did not equal or exceed the threshold of 1352 counts per minute, for a minimum duration of six minutes per day, data for that individual was excluded from the study. While such an exclusion may bias against individuals with low activity counts due to factors such as pain, this was necessary to create a natural version of the six-minute walk test, which traditionally requires six-minutes of continuous walking, with no breaks included.

2.2.4 Step count

To estimate forelimb step count within the six-minutes of highest continuous activity per dog, per day, the pedometer algorithm defined by Ladha et al (2018) was adjusted, removing the use of a rotation correction, translated to implementation within R (R Studio Team 2020), and applied to each of the previously defined six-minute windows using R (R Studio Team 2020). While the pedometer algorithm described by Ladha and colleagues begins by implementing a correction to remove the effects of collar rotation in the sagittal plane, I found that use of such a correction removed signals resulting from stepping movements, leading to an underestimation of step count, therefore this stage of the step detection algorithm was not implemented. While the occurrence of collar rotation cannot be ruled out due to a lack of supporting video footage, it is possible that the described correction was too strict when applied to data collected by Axivity AX3 devices and is perhaps more suitable when implemented with the VetSens (UK) devices used by Ladha and colleagues. To maintain all signals necessary for an reliable estimation of step count, rotation correction was therefore not included in the adjusted pedometer algorithm applied in this chapter.

For the first stage of the pedometer algorithm, R (R Studio Team 2020) was used to load and trim resampled accelerometer data according to the pre-defined six-minute durations for each recorded day. Trimmed data were then filtered with a 4th order, low pass Butterworth filter, designed to smooth the accelerometer signal by removing interference from frequencies which fell below the pass band (0.2Hz). Next, a zero threshold was applied to the dorso-ventral (Z) axis in rolling increments of 20 seconds. As accelerometer data were sampled at 100Hz, application of a zero-threshold involved applying a rolling mean at intervals of 200 data points, before subtracting each mean value from all data points in the 20 second window.

The next stage of the pedometer algorithm involved identifying and storing times in which the zero threshold was crossed, giving an initial step count. Crossing of the zero threshold occurred each time accelerometer data underwent a sign change, with negative sign changes indicating a potential step, referenced as step candidates by Ladha and colleagues. Step candidates were then filtered against an expected step frequency, for which the published pedometer algorithm implemented equation 2.2, described by Heglund et al (1974), whereby W = body mass (kg).

$$Stride\ frequency\ (min^{-1}) = 269W^{-0.14} \tag{2.2}$$

Weight was not consistently recorded for all individuals included in the existing dataset, meaning that minimum and maximum values could not be reliably extracted for the application of equation 2.2. As Ladha and colleagues based their expected step frequency on a large body weight range (11.3Kg – 64Kg), by which individuals in the existing dataset were likely to be encompassed, the defined frequency of 2.25-3.75Hz was considered, before implementing a margin. As the published pedometer algorithm was defined using a cohort of control dogs, while the existing dataset included control and arthritic individuals, an additional margin was required to allow for potential irregularities in step frequency resulting from OA, and the expected frequency was therefore rounded to 2-4Hz. It was expected that inclusion of a margin in the expected step frequency would also compensate for the lack of weight data, ensuring that any individuals beyond the weight range specified by Ladha and colleagues were represented accordingly.

To ensure step candidates were within the expected frequency of 2-4Hz, a one-second window was applied, within which the number of step candidates were recorded. Windows containing step candidates outside of the expected frequency were identified and deleted, removing these candidates from the filtered step count. The final stage involved filtering against irregular movements such as shuffles. To locate non-stepping movement i.e. those which fell beyond the expected frequency of 2-4Hz, the time between each perspective step was identified using a rolling window of 10 step candidates, before highlighting those that did not fall within 0.25 and 0.5 seconds of each other. Windows were deleted if the number of highlighted candidates exceeded three, removing these candidates from the filtered step count, as justified above, based on the expected step frequency of 2-4Hz. Both initial and filtered step counts were recorded, before calculating irregular steps and shuffles by subtracting the filtered count from the initial count.

2.2.5 Video Validation

A validation exercise was required to assess the translation and implementation of code developed throughout this study, whereby only a small sample size was required due to previous validation of the defined algorithm by Ladha and colleagues (2018). For the validation exercise, accelerometer data recorded from four dogs (table 2.1.) with supporting video footage was used to compare steps counted manually with those detected using the defined algorithm. To manually count steps, ELAN (Version 6.2) was first used to match the start and end points of the video footage with the paired accelerometer signal. Matching the accelerometer signal and video footage was made possible as the action of clapping hands around the accelerometer before and after data collection had been recorded, resulting in characteristic peaks and troughs in the Z axis of the acceleration data (figure 2.1) which could be paired with the corresponding section of video.

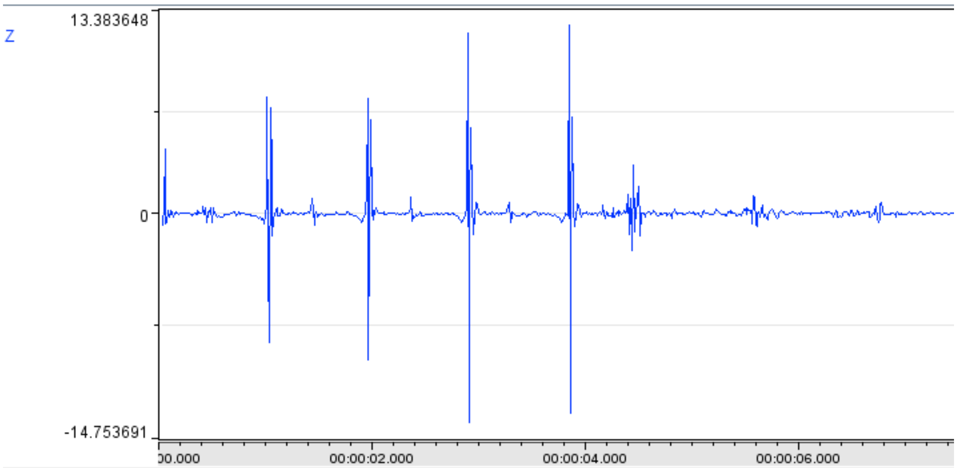


Figure 2.1. Screenshot of an accelerometer signal displayed in the software ELAN (Version 6.2), with characteristic peaks and troughs resulting from hands clapping around an accelerometer.

Video footage and acceleration data were then trimmed to include only sections where all four paws were visible, ensuring no steps or gait irregularities were missed, and the number of steps taken by each forelimb was recorded. Trimmed acceleration data were then loaded using R (R Studio Team 2020), before applying the pedometer algorithm and recording the initial and filtered step counts for each dog. R^2 was then used to explore the relationship between the manual step count and the step count generated by applying the pedometer algorithm.

2.2.6 Statistical Analysis

Step count was considered in three categories (Figure 2.2), including the initial step count and the filtered step count, as well as irregular steps and shuffles.

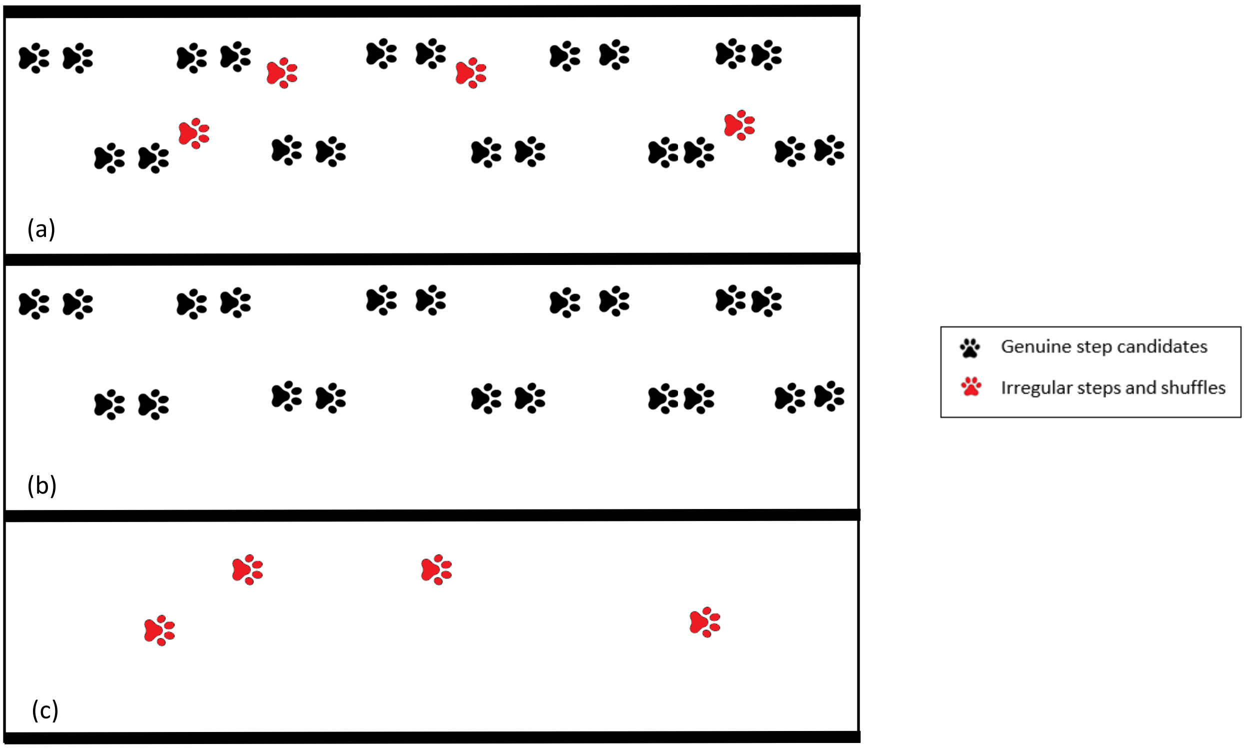


Figure 2.2. Diagrammatic representation of the three step count categories, Initial step count (a), including genuine step candidates with irregular steps and shuffles; filtered step count (b), including only genuine steps; and irregular steps such as shuffles (c).

To investigate the relationship between the three step count categories, OA, and age, Linear mixed effects (LME) models were selected, with the implementation of such models enabling the consideration of random effects, as well as the inclusion of repeated measures with no reduction in statistical power (Baayen et al 2008). In the first model, OA was included as the independent variable, while each step count category was entered (in turn) as a dependent variable, before setting dog ID as a random effect. Models were then repeated to include age as the independent variable before final models included both age and OA. LME models were based on equation 2.3, expressed by Laird and Ware (1982).

$$y_i = X_i\alpha + Z_i b_i + e_i \tag{2.3}$$

Due to the positive correlation between age and OA (whereby the prevalence of OA increases with age), it was reasonable to consider that collinearity could be present between the two variables. The potential presence of collinearity would ensure that the effects of age and OA could not be separated, perhaps causing inflated standard errors and unreliable tests of significance (Dormann et al 2012).

As collinearity was suspected between OA and age, the use ridge regression models were required. For each step count category, a mean value and standard deviation was extracted per dog, per day. Ridge regression models were then constructed to include both age and OA as independent variables, with the mean and standard deviation for each step count category entered in turn as dependent variables. For each ridge regression model, optimal lambda values were selected from a predefined sequence of zero to 100, with increments of 0.1. This was achieved using the cross-validation function within the 'glmnet' package, before noting the value with the lowest mean cross-validated error. The process was repeated 100 times for each model, and the mean of all noted values was calculated and included in the ridge regression model as the optimal lambda value. Use of the ridge regression models enabled further investigation into the relationship between age, OA, and each of the three step count categories, while addressing the potential impact of collinearity. This is achieved by introducing a degree of bias to model estimates, reducing variation, while improving the reliability of predictions (Melkumova and Shatskikh 2017).

Next, data were subset to include only arthritic individuals, and LME models were used to explore the relationship between LOAD score (an indicator of OA severity), and the three step count categories. Categories (including initial step count, filtered step count and the irregular steps and shuffles) were entered in turn as dependent variables, while LOAD score was included as the independent variable, with dog ID as a random effect. To avoid obtaining a singular fit, an indicator that corelations between random effects are approximated close to 1 or -1, leading to a lack of reliability in model outputs (Oberpriller et al 2022), the associations between LOAD score and the three step count categories were then further explored using Bayesian LME models. Step count categories were used in turn as dependent variables, while LOAD score was entered as the independent variable, with dog ID and day both included as random effects. An ANOVA test was then used to test for significance when comparing the null and alternative models.

Next, the mean activity counts of sound and arthritic dogs were explored using descriptive statistics. As a large degree of variation in mean activity counts both within and between groups was highlighted, a factor which could hinder the interpretation of LME models by inflating standard error, the use of scaling and re-centering was made necessary.

By applying the 'scale' function within R's 'base' package, mean activity counts were first re-centred by subtracting the column mean from all datapoints before being scaled via the division of centred datapoints by their standard deviations. Scaling of the mean activity counts allowed for normalisation of the recorded values, while maintaining the output of subsequent LME models.

The relationship between OA, age and activity counts could then be investigated using LME models. In the first model, OA was included as the independent variable, while activity counts were entered as a dependent variable, before setting dog ID as a random effect. Models were then repeated to include age as an independent variable, before including both age and OA. Finally, data were subset to include only arthritic individuals and an additional LME model was used to explore interactions between LOAD score and activity counts, whereby LOAD score was set as the independent variable, with activity counts as a dependent variable and dog ID as a random effect. All statistical analyses were performed using R, version 3.6.0, and a significance value of p=0.05 was selected for all models.

2.3 Results

2.3.1 Pedometer validation

As a result of trimming accelerometer data to match corresponding sections of video whereby all four paws of the dog were visible, the accelerometer signal of three dogs was reduced to three minutes, while the signal of one dog was reduced to just one minute (table 2.2).

Table 2.2. Summary of steps counted manually, as well as those generated by the pedometer algorithm, using the validation dataset. Filtered pedometer steps are presented to the nearest 10 steps due to the implementation of a 10-step window during the filtering stage of the pedometer algorithm.

Dog ID	Recording duration (minutes)	Manually counted steps	Initial pedometer steps	Filtered pedometer steps
C002FGK	1	218	236	230
C008FGK	3	657	685	500
C005MGK	3	542	551	500
C009MGK	3	602	593	580

When compared to manually counted steps, the initial step count was overestimated in all but one dog (C009MGK), whereas the filtered step count provided an underestimation of steps in all but one dog (C002FGK). The manually obtained step count explained approximately 99% of the variability in the initial step count generated by the pedometer algorithm (R^2=0.994). The filtered step count was slightly less reliable, however the manually obtained step count still explained approximately 88% of the variability in this variable (R^2=0.889).

2.3.2 Mean pedometer step counts

The mean values for initial step count, filtered step count and irregular steps and shuffles were marginally greater for dogs with a confirmed diagnosis of OA (Table 2.3).

Table 2.3. Mean values for initial step count, filtered step count, and the irregular steps and shuffles, calculated for control and arthritic dogs.

	Initial Step count (mean)	**Filtered step count (mean)**	**Irregular steps and shuffles (mean)**
Control	1058(±46.62 SD)	917 (±70.35 SD)	143 (±86.43 SD)
OA	1064 (±48.73 SD)	919 (±74.49 SD)	144 (±66.10 SD)

While the between group variation was marginal across all step count categories (Figure 2.3), the greatest difference was found in the initial step count, whereby a mean value of 1064 steps (±46.62 SD) were detected from arthritic dogs, compared to the mean value of 1058 steps (±48.73 SD) detected from their control counterparts. As the described difference in the mean step count is so marginal, it is unlikely to be statistically significant. Comparatively, the greatest extent of within group variance was noted in the irregular steps and shuffles of the control group, with a mean value of 143 steps (±86.43 SD).

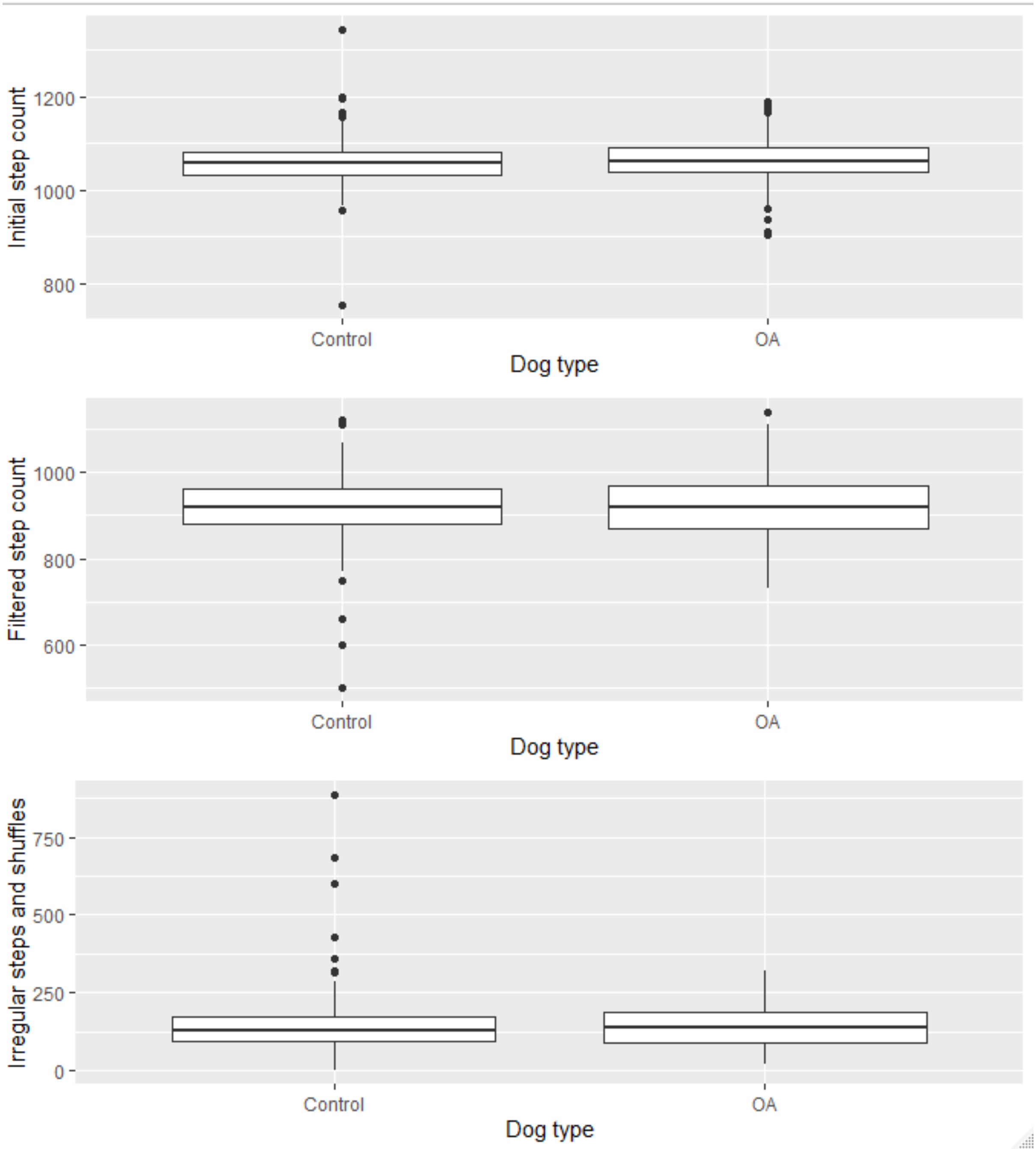


Figure 2.3. The degree of variation in the three step count categories for control and arthritic dogs.

2.3.3 The relationship between osteoarthritis, age, and the three step count categories

No significant association was found between the step count categories and age, with P>0.05 in all models (Table 2.4.). Similarly, no significant association was detected between the step count categories and a confirmed diagnosis of OA.

Table 2.4. Summary of Linear Mixed Effects models exploring the relationship between age, OA, and step count categories.

Independent variable	Dependent Variable	Random Effect	Estimate	P Value	T Value	Std. Error	DF
Age	Initial Step Count	Dog ID	1.323	0.160	1.421	0.931	69.41
OA	Initial Step Count	Dog ID	5.518	0.464	0.736	7.495	70.07
Age and OA	Initial Step Count	Dog ID	1.424 (Age) -1.340 (OA)	0.231 (Age) 0.887 (OA)	1.210 (Age) -0.143 (OA)	1.177 (Age) 9.376 (OA)	68.19 (Age) 68.74 (OA)
Age	Filtered Step Count	Dog ID	-0.548	0.684	-0.409	1.340	69.57
OA	Filtered Step Count	Dog ID	2.307	0.830	0.216	10.687	70.25
Age and OA	Filtered Step Count	Dog ID	-1.139 (Age) 7.792 (OA)	0.503 (Age) 0.565 (OA)	-0.674 (Age) 0.578 (OA)	1.691 (Age) 0.578 (OA)	68.34 (Age) 69.00 (OA)

Age	Irregular steps and shuffles	Dog ID	1.877	0.164	1.407	1.334	69.57
OA	Irregular steps and shuffles	Dog ID	1.196	0.912	0.111	10.784	70.49
Age and OA	Irregular steps and shuffles	Dog ID	2.812 (Age) -12.347 (OA)	0.098 (Age) 0.359 (OA)	1.678 (Age) -0.924 (OA)	1.676 (Age) 13.363 (OA)	68.28 (Age) 69.15 (OA)

When considering the large degree of standard error in the LME models, as well as the known correlation between age and OA, it was thought that collinearity could be present between the two independent variables, making the potential association between age, OA, and the step count categories unclear.

2.3.4 Ridge Regression

Ridge regression models were applied in response to the potential presence of collinearity. As with the LME models, no significant interactions were detected between age, OA and the step count categories, $P>0.05$ across all models (Table 2.5.).

Table 2.5. Summary of Ridge Regression models exploring the relationship between age, OA, and the step count categories.

Independent Variable	Dependent Variable	Lambda Value	Estimate	P Value	T Value	Standard Error
Age and OA	Initial step count (mean)	92.4401	0.039 (Age) 0.058 (OA)	0.162 (Age) 0.466 (OA)	1.399 (Age) 0.729 (OA)	3.293×10^{-1}
Age and OA	Filtered step count (mean)	100	-0.006 (Age) 0.024 (OA)	0.670 (Age) 0.818 (OA)	0.426 (Age) 0.230 (OA)	0.43277
Age and OA	Irregular steps and shuffles (mean)	71.52874	0.026 (Age) 0.012 (OA)	0.161 (Age) 0.935 (OA)	1.403 (Age) 0.082 (OA)	0.60610
Age and OA	Initial step count (sd)	100	0.002 (Age) 0.002 (OA)	0.757 (Age) 0.962 (OA)	0.309 (Age) 0.047 (OA)	0.188216
Age and OA	Filtered step count (sd)	76.61862	0.015 (Age) 0.047 (OA)	0.145 (Age) 0.562 (OA)	1.458 (Age) 0.581 (OA)	0.33590

Age and OA	Irregular steps and shuffles (sd)	20.87533	0.034 (Age) -0.473 (OA)	0.522 (Age) 0.273 (OA)	0.641 (Age) 1.097 (OA)	1.79466

2.3.5 The relationship between LOAD score and the three step count categories

When considering the relationship between LOAD score and the step count categories, no significant interactions were indicated when entering dog ID as a random effect, P>0.05 across all LME models (Table 2.6.). To avoid obtaining a singular fit, relationships were further explored using Bayesian linear mixed effects models.

Table 2.6. Summary of Linear Mixed Effects models exploring the relationship between LOAD score, and the step count categories.

Independent Variable	Dependent Variable	Random Effect	Estimate	P Value	T Value	Standard Error	DF
LOAD Score	Initial step count	Dog ID	-0.617	0.47	-0.73	0.846	39.0151
LOAD Score	Filtered step count	Dog ID	-0.542	0.669	-0.431	1.256	38.996
LOAD Score	Irregular steps and shuffles	Dog ID	0.700	0.623	0.496	1.405	39.0025

2.3.6 The relationship between LOAD score and the three step count categories - Bayesian linear mixed effects models

Comparison of the Bayesian LME models did not support the use of the alternative model, suggesting that relationships between LOAD score and the three step count categories were not significant P>0.05 across all ANOVA tests (Table 2.7.).

Table 2.7. Summary of Bayesian Linear Mixed Effects models exploring the relationship between LOAD score, and the step count categories.

Independent Variable	Dependent Variable	Random Effect	Estimate	Standard Error	T Value	ANOVA Test P Value
LOAD Score	Initial Step Count	Dog ID & Day	-0.7965	0.6110	-1.304	0.1836
LOAD Score	Initial Step Count (null model)	Dog ID & Day	1063.877	6.746	157.7	
LOAD Score	Filtered Step Count	Dog ID & Day	-1.3845	0.8392	-1.65	0.09429
LOAD Score	Filtered Step Count (null model)	Dog ID & Day	919.943	9.617	95.66	
LOAD Score	Irregular Steps and Shuffles	Dog ID & Day	0.6347	0.7498	0.847	0.3829
LOAD Score	Irregular Steps and Shuffles (null model)	Dog ID & Day	144.309	8.651	16.68	

2.3.7 Mean activity counts

Of the mean activity counts noted for control dogs, a mean value of 7807.63 counts per minute (±2886.83 SD) was calculated, compared to a lower mean value of 5538.40 counts per minute (±2336.14 SD) calculated for the arthritic group, highlighting a large degree of variation both within and between groups (figure 2.4). Although extreme outliers were present the arthritic group, it was not possible to ascertain whether these data points were anomalous or in fact representative of legitimate observations, and therefore the outlying datapoints were preserved within the dataset for inclusion in LME models.

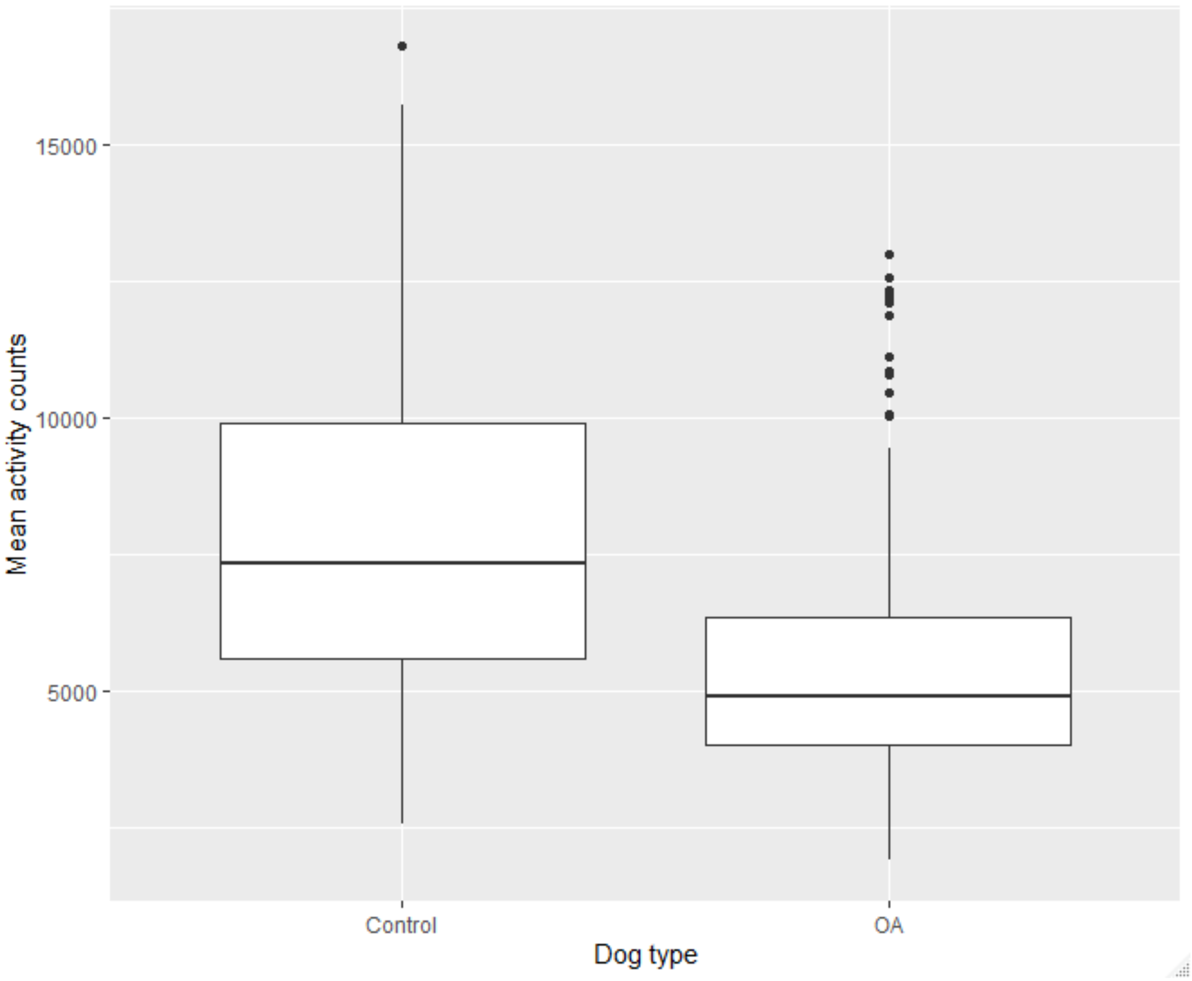


Figure 2.4. The degree of variation in mean activity counts for control and arthritic groups.

2.3.8 The relationship between osteoarthritis, age, and activity counts

The mean activity counts of control dogs was significantly higher than those of arthritic dogs during the six minutes of highest continuous activity per day ($P=4.24 \times 10^{-5}$, $t=-4.368$, Std Error = 0.18 df=70.22) (figure 2.5).

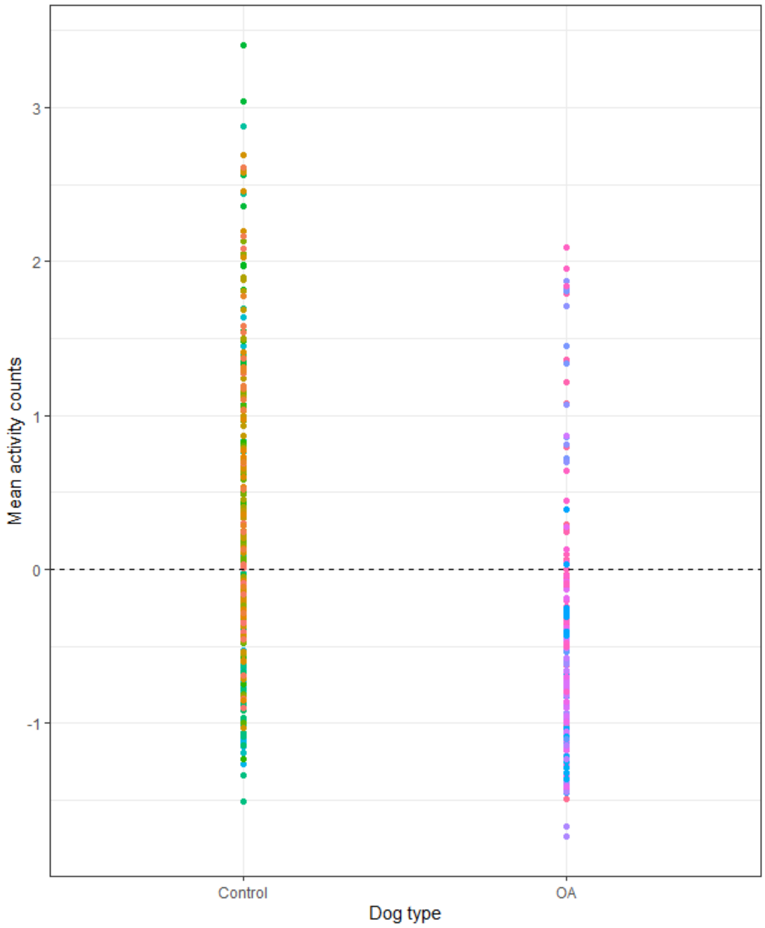


Figure 2.5. The association between activity counts and osteoarthritis, whereby each coloured marker is representative of an individual within the control or osteoarthritic cohort.

Significant interactions were also noted between age and the mean activity counts recorded during the six minutes of highest continuous activity per day ($P=3.02\times10^{-7}$, t=-5.666, std Error = 0.021, df=69.94) (Figure 2.6).

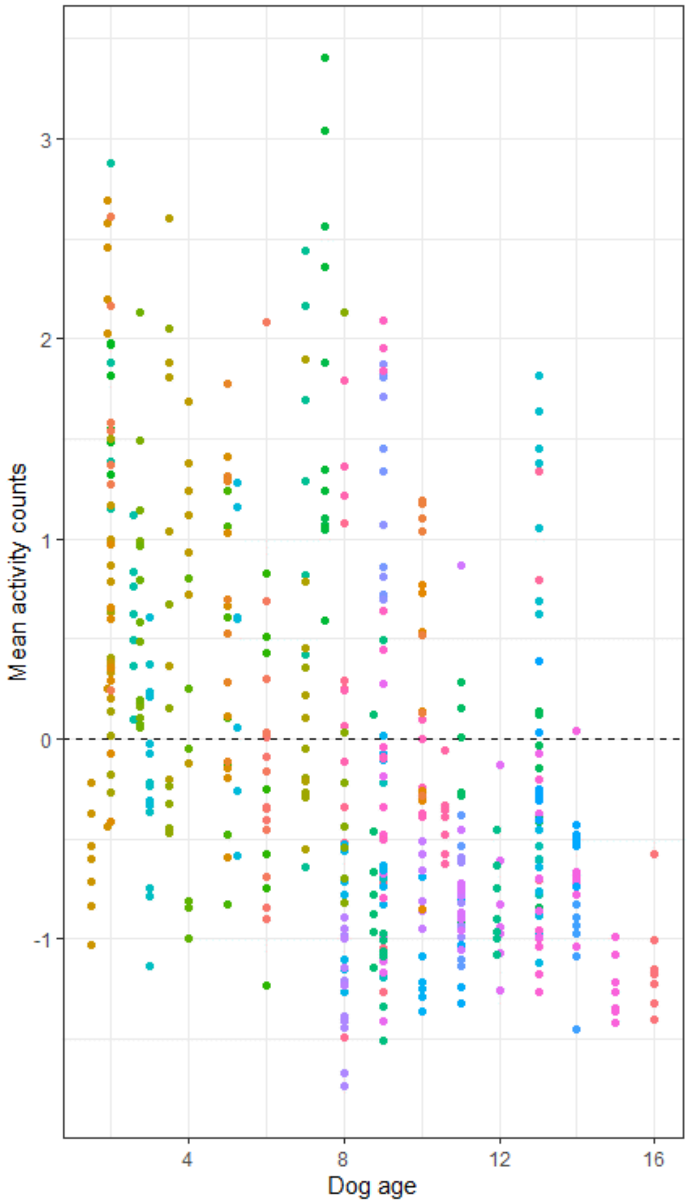


Figure 2.6. The association between mean activity counts and age, whereby each coloured marker is representative of an individual within the control or osteoarthritic cohort.

Although the inclusion of both age and osteoarthritis as predictors in a univariate model highlighted a significant interaction between age and mean activity counts, a reduction in significance was noted for both variables when compared with univariate models (P = 0.118, t=-1.583, df=69.13, std Error =0.21; P= 0.000594, t=-3.601, df=68.86, std Error = 0.026 for OA and age respectively).

2.3.9 The relationship between LOAD score and activity counts

Exploration of subset data including only arthritic individuals highlighted no significant interactions between mean activity counts and osteoarthritis severity (LOAD score), whereby P=0.119, t= -1.609, df=27.04 and std Error = 0.012 (figure 2.7).

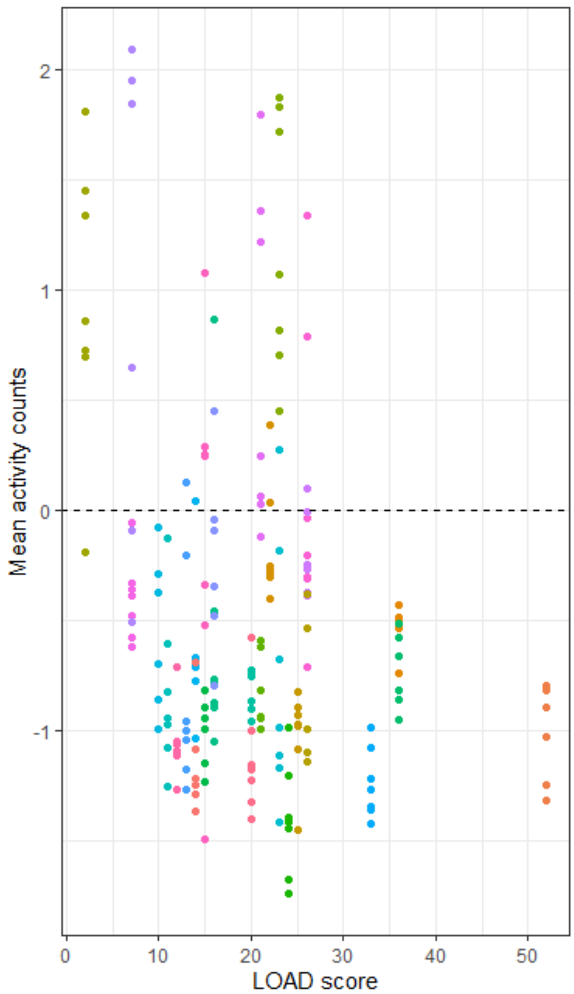


Figure 2.7. The association between mean activity counts and LOAD score, whereby each coloured marker is representative of an individual within the osteoarthritic cohort.

2.4 Discussion

We created a natural version of the 6MWT using an existing accelerometer dataset, collected from sound and arthritic dogs across six and seven day durations. The modified 6MWT encompassed the six minutes of highest continuous activity identified per dog per day, from which mean activity counts were extracted and step count was estimated in three categories, initial step count and filtered step count, as well as irregular steps such as shuffles. While a small-scale validation exercise showed a high association between the initial step count and steps counted manually, this association reduced when considering the filtered step count. Although no interactions were detected between osteoarthritis and the three step count categories, mean activity counts recorded during the defined six-minutes differed significantly between the osteoarthritic and control dogs, and while activity counts were associated with age, no significant relationship was detected with osteoarthritis severity.

A small-scale validation exercise was used to assess the translation and implementation of code developed throughout this study. As the pedometer algorithm was previously validated by Ladha and colleagues (2018), a more extensive validation was not neccessary. While a reasonable degree of reliability was noted for all step count categories, steps were consistently underestimated when eliminating irregular movements such as shuffles, suggesting that the filtered step count was too conservative, indicating the need for further validation. As the validation dataset was limited to four sound dogs, for which the accelerometer and video recordings had brief durations of approximately three minutes, further validation would require a more substantial dataset, recorded from an increased sample size. Additionally, it was not possible to evaluate the precision of the filtered step count for dogs with gait abnormalities including osteoarthritis, as no arthritic individuals were included in the validation dataset, while the published algorithm was designed based on a cohort of clinically sound dogs. To better gauge the reliability of the filtered step count for arthritic dogs, use of a more diverse validation dataset would be required, including individuals with a range of conformations and gait abnormalities, including osteoarthritis.

No significant differences were noted when comparing the step counts of sound and arthritic dogs, a result which may indicate the inclusion of well managed individuals within the osteoarthritic group. The management of osteoarthritis can involve interventions such as pain-relieving medications, as well as careful control of exercise and body weight (Pettitt and

German 2015). Although the use of interventions can supress clinical signs of osteoarthritis including lameness (Vaughan-Scott and Taylor 1997), use of interventions including pain relieving medications within the osteoarthritic group was not determined, and as such, the associated impacts on the estimated step counts could not be ascertained. Step counts may be further influenced by activity intensity, which could vary based on the use of a leash, and the terrain upon which the individual was exercised. Although details of exercise sampled by the modified 6MWT could not be confirmed due to a lack of supporting video footage, step count was estimated from the six minutes of highest continuous activity per day, throughout which it was considered that a portion of the dog's daily exercise would be encompassed, whereby the intensity of activity would reflect individual tolerances. Although it is likely that estimated step counts were influenced by individual variation in exercise capacity, the extent to which owner management and condition severity impacted the exercise tolerance of arthritic dogs remains unclear. Although the severity of osteoarthritis can be considered in four categories including mild, moderate, severe, and extreme (University of Liverpool 2017), based upon the calculated LOAD score, only four of the sampled arthritic dogs occupied the extreme category. As such, the lack of relationship between osteoarthritis and step count may be due the overrepresentation of individuals with low disease severity. When further considering the proportion of individuals with mild and moderate osteoarthritis, it becomes reasonable to question whether six minutes of activity was sufficient to elicit gait abnormalities associated with the disease. As osteoarthritis-related gait irregularities are often intermittent (Belshaw et al 2020a) and dependent on factors such as exercise duration and intensity (Vaughan-Scott and Taylor 1977), it is possible that well-managed individuals, as well as those with low disease severity, may be capable of more intense activity across extended durations. The inclusion of high functioning and well managed individuals could influence the lack of relationship between osteoarthritis and step count by generating a ceiling effect, the plausibility of which is indicated when recording distance travelled in human studies (King et al 2020). To account for variability in individual exercise tolerances, as well as the potential effects of condition management, a longitudinal study may be more appropriate, with repeated 6MWTs conducted before and after a confirmed diagnosis of osteoarthritis, or the provision of interventional treatment.

Associations were noted between osteoarthritis and activity counts, whereby significantly reduced counts were recorded by arthritic individuals. While a reduction in activity counts indicated lower energy expenditure when taking steps, the degree to which this was due to osteoarthritis remains unclear. Although no further interactions were identified when exploring the relationship between activity counts and osteoarthritis severity, associations with age were detected, indicating that activity counts cannot be used in isolation to distinguish osteoarthritic individuals from their sound counterparts, confirming the limited diagnostic potential for this parameter. Although the relationship between osteoarthritis severity and activity counts may be distorted by the limited inclusion of individuals with high LOAD scores, energy expenditure when stepping may instead be due to the age of the individual. Despite this, Lee et al (2022) highlighted a lack of clarity regarding the degree to which interactions between age and physical activity are influenced by the behaviour of the owner. Owners may expect a reduction in physical activity and fitness as their dog ages, a view which could arise from the age-related normality of certain health disorders such as osteoarthritis (Packer et al 2012; Lascelles et al 2002), perhaps leading to a decline in the provision of structured exercise. As the accelerometer data were not supported by video footage and no owner testimony was collected to confirm the provision and duration of exercise, it was not possible to determine the impact of owner behaviour on the recorded activity counts.

Additional factors which could influence interactions between age and activity counts include comorbidities. Once diagnosed, canine osteoarthritis is one of four notable conditions (including obesity, diabetes mellitus and hyperthyroidism) that are associated with an increased risk of developing comorbidities (Hoffman et al 2018), the potential for which is enhanced with age (Jin et al 2016; Hoffman et al 2018). Each of the specified conditions are associated with changes in physical activity, whereby restlessness is reported in case studies of canine hyperthyroidism (Maunder et al 2018), while lethargy is observed in individuals diagnosed with diabetes mellitus (Catchpole et al 2005). Similarly, obesity may be associated with reduced physical activity (Chapman et al 2019), with the potential to increase the prevalence of locomotor and musculoskeletal conditions such as osteoarthritis (Sanderson 2012). Although the estimated prevalence of diabetes mellitus and hyperthyroidism among pedigree dogs in the UK is low, affecting around 0.15% to 0.53% of dogs respectively (Wiles et al 2017), obesity is more frequently observed, impacting approximately 34-59% of companion dogs in the UK (German 2014). Due to the prevalence of common comorbidities, particularly obesity, the potential inclusion of individuals with multiple health concerns cannot be discounted. As comorbidities are associated with altered physical activity, their potential impact on the observed relationship between activity counts and age remains unclear. When accounting for age related factors such as comorbidities, the importance of controlling the effects of age during accelerometer studies becomes apparent. Although controls for age were implemented within the statistical analyses, a more reliable interpretation of interactions may require an age matched study design. Despite this, the prevalence of osteoarthritis in 80% of dogs exceeding the age of eight (Anderson et al 2018), and 20% of dogs exceeding the age of one (Fritsch et al 2010) may make such a study infeasible, owing to the potential inclusion of individuals with undiagnosed osteoarthritis.

The study was further limited by a lack of demographic information for sampled dogs, meaning it was not possible to establish whether the sample was representative of a range of breeds and conformations. Despite this, it is understood that the number of steps required to travel a specified distance is associated with the size of the animal, whereby taller, heavier dogs will have a lower stride frequency than those who are smaller (Heglund et al 1974). As height is determined somewhat by breed, it is possible that over representation of single breeds, such as those with chondrodysplasia, a trait characterised by disproportionally short limbs (Smolders et al 2013), could influence the perceived relationship between step count and osteoarthritis. While breed information was available for individuals included in the validation dataset, this was comprised of just four dogs, belonging to three large breeds: Greyhound, Rhodesian Ridgeback and Irish Wolfhound, meaning the reliability of automatic step detection cannot be established for smaller breeds, which may have been sampled in the seven-day dataset. To enhance the sensitivity of the step detection algorithm across a range of conformations, Chambers et al (2021) highlights the importance of large validation datasets, encompassing a diverse variety of breeds.

The sensitivity of the step detection algorithm was also restricted by inconsistent availability of weight data for sampled dogs. A key stage in the automated step detection involved filtering step candidates against an expected step frequency, which is typically calculated using the body weight of the individual, as described by Heglund et al (1974). As body weight was not available for all sampled dogs, a large weight range was implemented, with an additional margin of error for the inclusion of osteoarthritic individuals. While it is expected that such a margin enabled step detection across a range of breeds and conformations, this could not be validated due to a lack of video footage in support of the accelerometer data.

The absence of video footage also limited the degree to which accelerometer data could be interpreted. While the pedometer algorithm was applied to a six-minute time series of activity with the highest representative activity count, it is unclear whether the bout of activity within the sampled window was continuous, or if this comprised of discrete bursts of high energy activity. The extraction of steps from non-continuous bouts of activity may have resulted in step counts which were not truly representative of the individual, due to the potential inclusion of rest periods within the six-minute window, reducing the time in which steps could be recorded. To ensure that step counts were generated from equal time durations for each dog across the seven-day duration, it may have been more appropriate to extract step counts from the six minutes with the greatest cumulative activity count per day, even if this involved stitching together non-continuous data.

Further advancement of the study could be achieved by investigating stride length as an indicator of distance travelled, using an inverted pendulum model, described by Ladha et al (2018). Investigation of distance travelled could provide further insight into the nature of the activity that took place throughout the six-minute windows potentially reducing the degree to which the study was limited by a lack of supporting video footage. Furthermore, distance travelled could be used to establish an individual's walking capacity, whereby score variation in human arthritis studies is reflective of chronic pain (King et al 2022), perhaps offering an alternative parameter which is sensitive to osteoarthritis related gait abnormalities in dogs.

When exploring alternative methods for detecting osteoarthritis in dogs, the opinion of experts should be considered. This could be achieved with the use of the Delphi consultation process, a method which enables the exploration of expert opinion, using a series of questionnaires. Further work should therefore implement the Delphi consultation process to identify priority gait parameters for measurement, based upon a pre-defined level of consensus from a panel of veterinary healthcare professionals. In addition to investigating alternative parameters for detecting osteoarthritis, further work should be undertaken to assess the reliability of automated step counts for arthritic dogs, by validating the step detection algorithm for individuals with diagnosed osteoarthritis at varying stages of severity, using video footage to support the interpretation of accelerometer data. Further validation should also be undertaken for healthy dogs, whereby the reliability of pedometer generated steps should be assessed across a range of gaits and controlled speeds, which may have been sampled during the modified 6MWT. Additional work should also assess the dynamics of activity counts and walking over different timescales, including continuous walking as well as discrete bursts of activity, providing clarity on whether step count should be extracted from stitched data, as opposed to continuous windows. Similarly, a longitudinal study should assess the potential use of activity counts as a means of monitoring arthritis severity, by investigating the overall reduction in activity for dogs as they age, or receive an osteoarthritis diagnosis, with consideration for the impacts of owner behaviour.

2.5 Conclusion

The use of accelerometers for osteoarthritis detection first requires the identification of measurable gait parameters from which condition specific abnormalities can be detected. While extensive validation of the diagnostic potential for such parameters would be required, longitudinal mapping of changes could be useful for monitoring the progression of chronic conditions, as well as assessing the effectiveness of treatment. While the observed interactions between activity counts, osteoarthritis and LOAD score demonstrate the potential use of activity counts derived during the six-minute walking test as a monitoring tool, additional associations with age mean this parameter would be unfit for use in a diagnostic capacity. To better understand the relationship between activity counts, age and osteoarthritis, baseline values should be established for a range of dogs, encompassing a variety of breeds, conformations, and ages, before tracking deviations in these values over time.

While there is more to explore when considering the potential use of accelerometers for diagnosing and monitoring canine osteoarthritis, with a host of data to be extracted, it is important to prioritise investigation of those gait parameters most sensitive to arthritis related abnormalities, based upon expert opinion, which should be collected following a consensus-based approach, such as the Delphi Consultation process.

Chapter 3. The Use of Technology in Veterinary Therapeutics and For the Long-term Monitoring of Canine Osteoarthritis: A Delphi Consultation Study

3.1 Introduction

3.1.1 The pathway to diagnosis and effective treatment

For humans, companion animal ownership is associated with a range of benefits, including interspecies friendship and increased exercise (Westgarth et al 2017), reportedly leading to improved cardiovascular health, as well as reduced stress, anxiety, and depression (Surmer et al 2022; Martins et al 2023). Such benefits perhaps account for the increasing rate of pet ownership observed in the UK during the last ten years (McMillan et al 2024), whereby dogs and cats have been identified as the most popular species, each reaching populations of approximately 11 million individuals in 2023 (PDSA 2023). The welfare for each of these individuals is mandated by the Animal Welfare Act (2006), whereby owners have a responsibility to implement the five welfare needs, including freedom from injury and disease, whereby collaboration between owners and veterinarians is essential (Belshaw 2017). To facilitate an effective pathway to diagnosis and treatment, multiple steps must be taken by both vets and owners (Figure 3.1).

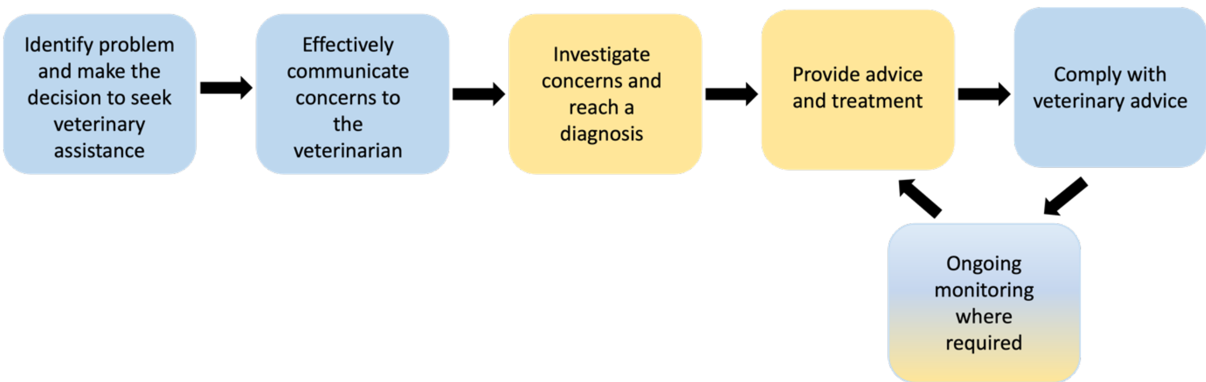


Figure 3.1. The steps required to facilitate an effective pathway to diagnosis and treatment. Boxes highlighted in blue show steps which must be taken by the owner, while boxes highlighted in yellow refer to steps that must be taken by a veterinarian, while boxes highlighted in blue and yellow indicate steps which must be taken by both owners and veterinarians.

3.1.2 Pitfalls in the pathway to diagnosis and effective treatment

While the series of steps can support the identification and treatment of injury and disease, this can be derailed by multiple factors, including the owner's ability to identify symptoms, the quality of appointments, the effectiveness of communication exchange, and the availability of alternative information (Belshaw et al 2020a; Mathews 2014; Roberts et al 2021; Stull et al 2018).

Collaboration between vets and owners first depends upon the owner's ability to identify a problem. Although a multitude of health complaints are often readily identifiable, such as parasitic infestations, skin complaints and injury (O'Neill et al 2021), some diseases such as osteoarthritis can be more difficult to detect. As the early stages of canine osteoarthritis, are often associated with subtle and intermittent symptoms (Belshaw 2017), there is potential for these indicators to be overlooked by owners (Belshaw et al 2020a), subsequently delaying their decision to seek veterinary assistance. Once the decision to seek veterinary attention is bypassed, there is scope for the unnoticed health concern to progress, before unexpected detection and diagnosis at routine and unrelated appointments, such as vaccinations (Cachon et al 2018). The receipt of such surprise diagnoses has the potential to blindside owners, perhaps reducing the extent to which they are willing to engage with their vet, while limited appointment times may limit the level of support and advice that can be offered in response.

Appointments in a general practice veterinary surgery are typically restricted to just 11 minutes (Robinson et al 2016). Within this time, the vet may take a history from the owner and perform a clinical exam, before effectively communicating their diagnosis and recommended treatment plan (Belshaw et al 2020a), with additional time constraints if vaccinations are to be administered. While 11 minutes may be sufficient in some instances, this could be dependent upon the owner's understanding of the information posed by the vet, whereby complex conditions and ineffective communication may necessitate further clarity, perhaps causing extended appointment durations. Where extended appointments are not feasible, the transfer of information between vets and owners may be interrupted, possibly leading to a dependency on alternative sources of information by owners (Belshaw et al 2016).

Owners have access to an abundance of veterinary healthcare information, across a range of sources, including forums hosted by social media platforms, other animal owners and books (Kogan et al 2018). While the quality of materials will vary between sources, vets could direct owners to reputable information by dispensing 'information prescriptions, a process which is applied in human healthcare (Brewster and Sen 2010). In lieu of such signposting, owners are required to identify quality information on their own behalf, a process which requires the critical appraisal of sources, the success of which will be influenced by the health literacy of the individual (Sørensen et al 2012). Although the use of quality information could enhance owner understanding of their pet's diagnosis and treatment, perhaps enabling more effective communication with vets, such materials may also lead to misplaced attempts at self-diagnosis.

3.1.3 The potential for sensor technology to address the pitfalls in the pathway to diagnosis and effective treatment

As stated, the maintenance of companion animal welfare, in line with The Animal Welfare Act (2006) requires collaboration between vets and owners to facilitate the effective treatment of pain, injury and disease. Despite this, a number of factors have been identified with the potential to obstruct cooperation between the two stakeholders, these include the owner's ability to identify symptoms, the quality of appointments, the effectiveness of communication exchange, and the availability of alternative information. When considering potential solutions to such pitfalls, the application of sensor technology should be considered.

The first stage of the diagnostic process requires the owner to detect condition specific abnormalities. While subtle symptoms associated with conditions such as osteoarthritis may evade owner attention (Mathews et al 2014), sensor technology has the potential to identify and track granular changes in biomarkers, as well as behavioural and activity parameters (Knight 2020), perhaps supporting the detection and longitudinal monitoring of otherwise overlooked health concerns. Once the decision to seek veterinary attention has been made, the owner must effectively communicate their concerns to the vet. While the subjective nature of owner observations can introduce difficulty at this stage, the use of accurate data recorded from relevant parameters could steer conversation and reduce the time taken to attain a thorough patient history, improving the quality of appointments. Similar applications are already observed in the management of livestock health, particularly cattle, whereby devices have the capacity to record health parameters before communicating these directly to vets (Knight 2020), supporting the first stage in the pathway to diagnosis and effective treatment. Next, the vet is required to reach a diagnosis and communicate this to the owner, detailing any necessary treatment. While ineffective communication could lead to a lack of compliance among owners, sensor technology could facilitate the provision of 'information prescriptions', supporting owner understanding of their pet's condition and treatment, while avoiding the use of misinformation. The final step in the pathway to diagnosis and treatment requires the owner to comply with veterinary advice. While a lack of noticeable improvement in their pet's physical condition may dissuade owners from implementing recommended treatment, granular changes in parameters measured by the sensor technology may increase trust and encourage compliance in veterinary advice. The ways in which technology could support the pathway to diagnosis and effective treatment are summarised in Figure 3.2

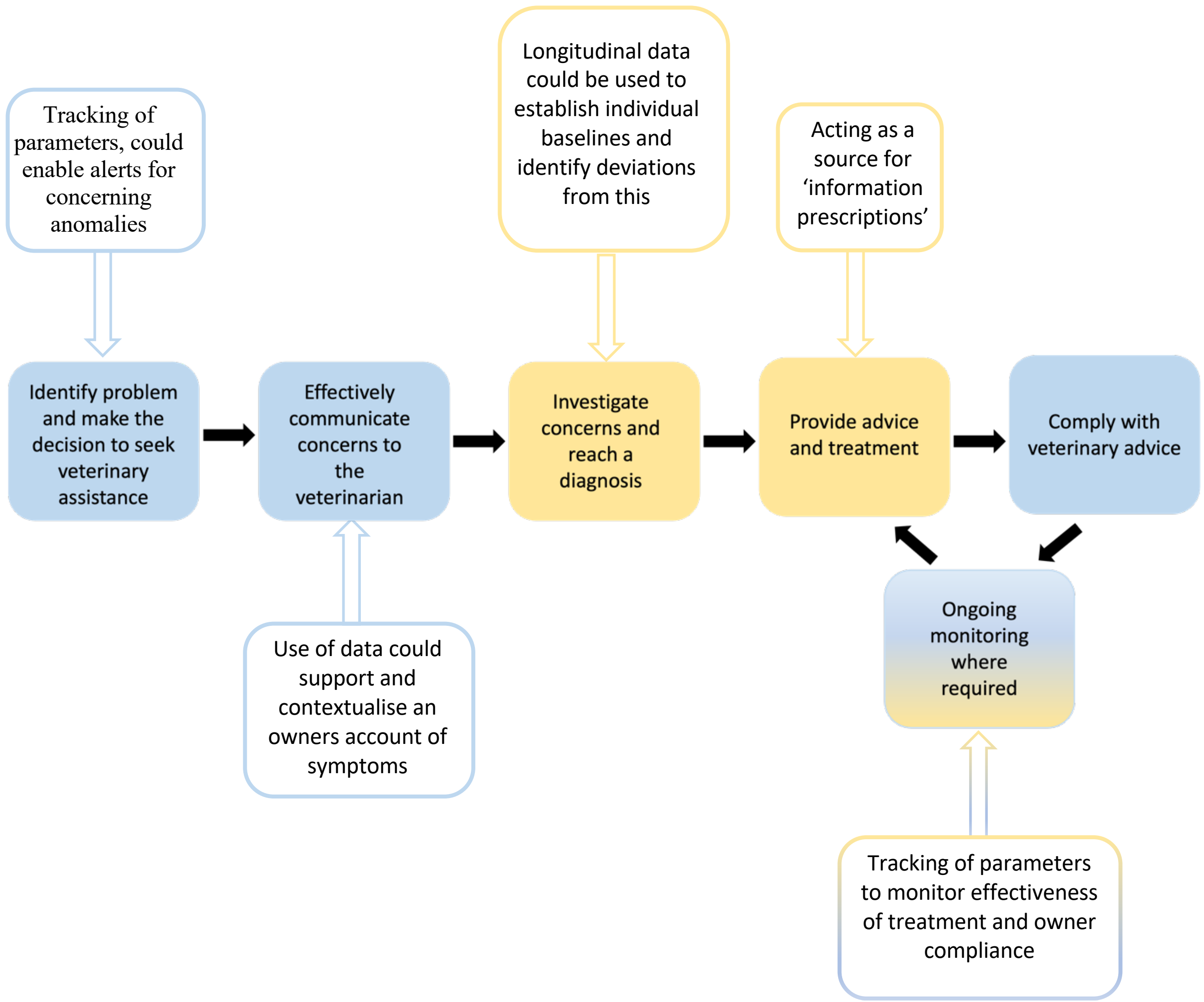


Figure 3.2. The ways in which sensor technology could support the pathway to diagnosis and effective treatment for chronic conditions.

3.1.4 A case study of novel technology

The use of sensor technology is increasing in popularity among animal owners, and while most commercial devices claim to monitor activities such as eating, sleeping, and walking (Carson et al 2023), those developed for use within veterinary healthcare, particularly among livestock, combine the measurement of biomarkers with activity and behaviour parameters. Such technology includes accelerometers as well as temperature, heart rate and pH analysis (Knight 2020) as well as a novel device proposed by Chordata Insight © (Chordata), which was used as a case study to explore the use of sensor technology for animal welfare, and diagnostic support between owners and vets.

The Chordata device seeks to integrate a multi-function injectable biosensor and ID chip, with a wearable ambient sensor, from which real time blood and ambient marker analysis will be conducted, measuring glucose and cortisol up to eight times per day. By analysing data collected by the device with machine learning algorithms, it is intended that health alerts will be generated for owners and vets when appropriate, informing early condition identification, while supporting rapid intervention and telehealth communications. While it is expected that such a device could be used to support the pathway to diagnosis by addressing the unmet needs of vets and owners, expert opinion surrounding the use of novel technology within veterinary healthcare is required.

The Delphi consultation process, described by Belshaw et al (2019) offers a method by which expert opinion can be collected using a series of questionnaires. The process typically begins with the identification of a problem area using relevant literature before raising the problem with a recruited panel of experts during a scoping meeting. The scoping meeting is used to confirm the need for investigation into the problem area, before filling any knowledge gaps which withstand following the initial review of literature. The final aim of the scoping meeting is to develop a questionnaire, designed to address the proposed problem. The resulting questionnaire is typically piloted by members of the target stakeholder groups, highlighting any necessary adjustments before issuing the questionnaire to participants. Responses are then collected, and the level of agreement among participants is assessed. Questionnaires are then redistributed, with this process repeating until agreement is reached at a pre-defined level of consensus. Use of the Delphi consultation process is particularly useful for addressing problems relating to animal health and welfare, due to the anonymity afforded to participants.

This study applies the Delphi consultation framework to seek expert consensus on the viability of sensor technologies applied to veterinary healthcare, before focussing more specifically on their potential use for the early detection and long-term monitoring of canine osteoarthritis.

3.2 Materials and Methods

3.2.1 Ethical Statement

All methods reported throughout this chapter were conducted following approval from Newcastle university's ethical review board (AWERB) Project ID No: ID 828, and 15712/2021.

3.2.2 Overview

The study applied the Delphi Consultation framework, adapted from Leach et al (2008) (Figure 3.3), to address the use of technology in veterinary therapeutics, as well as for the diagnosis and long-term monitoring of canine osteoarthritis.

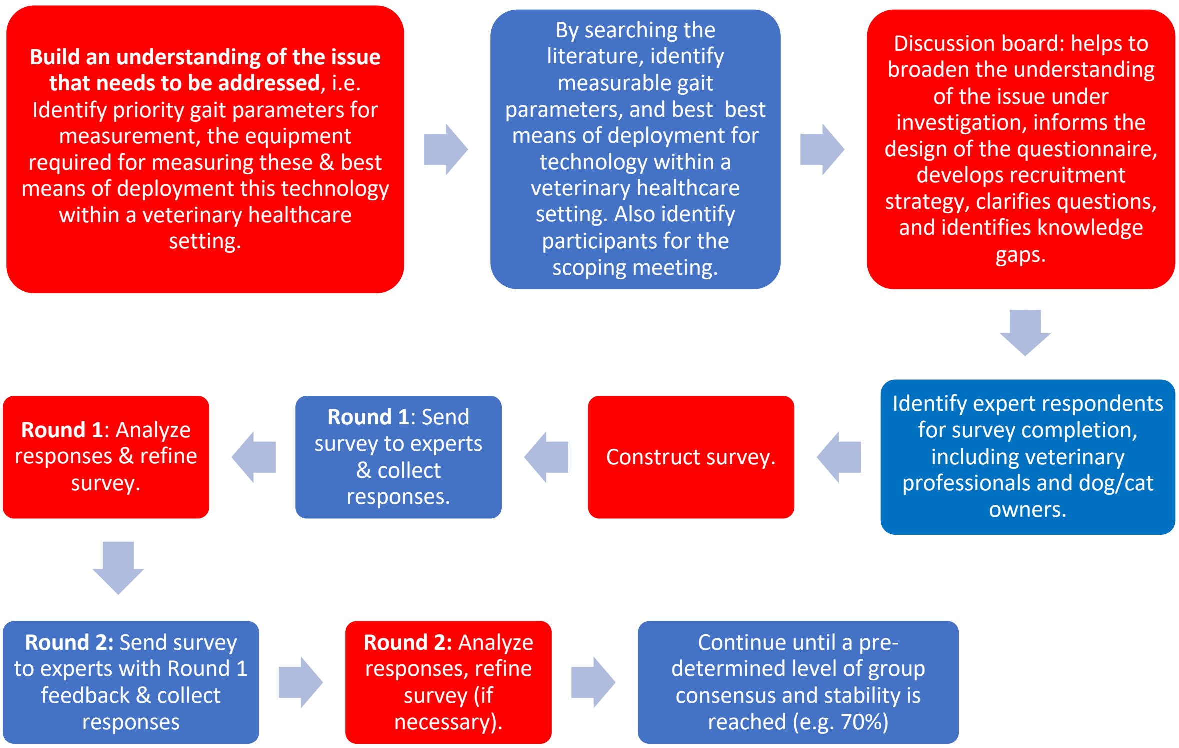


Figure 3.3 Delphi consultation framework, used to address the use of sensor technology in veterinary therapeutics, as well as for the diagnosis and long-term monitoring of canine osteoarthritis. Framework adapted from Leach et al (2008)

3.2.3 Literature search

The issue was first divided into two key themes, beginning with the use of sensor technology in veterinary therapeutics (theme 1), centring broadly upon potential methods for deploying novel technologies within the veterinary healthcare sector, before focusing upon the device posed by Chordata. The decision to focus solely upon the device posed by Chordata was made due to the fact that this device was still in development, meaning that no participants involved in the Delphi Consultation process had any experience of its use, whereby previous experience with the device may have influenced participant responses. Theme 2 then concentrated more specifically upon priority gait parameters for measurement to facilitate the diagnosis and long-term monitoring of canine osteoarthritis, as well as the technology required to record such parameters.

A literature search was then conducted, whereby human and canine gait analysis studies were sampled, to develop a broader understanding of the two key themes, while identifying and addressing any knowledge gaps. To do this, the Google Scholar search engine and Scopus database were used to search key terms and phrases, including but not restricted to: 'human gait', 'canine gait' and 'gait analysis protocol'. References were then filtered and identified for review by consideration of several factors, the first of which was number of citations, whereby a minimum of five were required. Such a threshold was established to ensure that only the most relevant literature was used to inform the content of the scoping meeting and subsequent questionnaires, while limiting the extent to which references would be excluded due to low citation numbers or recent publication date. The nature of the condition investigated was then considered (when applicable), whereby a range of conditions, including mechanical and neurological, were sought, to highlight condition specific variations in gait, or gait analysis protocols. A final consideration was the provision of parameter definitions. As parameter definitions can vary between studies and researchers, the provision of definitions was vital to the interpretation and potential reproducibility of methods. As such, the failure to define parameters led to the rejection of that study.

From each of the selected studies, gait parameters, their definitions, and required technology were extracted and recorded, while also noting methodological limitations and barriers, these would later be used to inform discussion throughout the scoping meeting stage.

3.2.4 Identification of expert respondents

For both of the key themes (use of sensors and parameters for OA detection), it was necessary to identify a target demographic, from which expert opinion would be sought throughout the scoping and survey stages of the study (Table 3.1).

Table 3.1 Target demographics for theme one and theme two.

Demographic group	Target Demographic	Theme(s)
Veterinary professionals	Veterinary surgeons	1&2
	Veterinary nurses	1&2
	Veterinary physiotherapists	1&2
	Veterinary hydrotherapists	1&2
Pet owners	Dog Owners	1
	Cat owners	1

For theme 1, it was decided that opinion should be sought from all potential stakeholders that may implement novel technologies in veterinary healthcare, while theme 2 would seek expert opinion from individuals involved in the diagnosis and monitoring of canine osteoarthritis. As both themes focussed on the implementation of technology, as opposed to its development, researchers were not considered to be a required stakeholder group and were not actively recruited. Despite this, responses received from researchers with experience of practicing as a veterinary professional were not excluded from the study due to their overarching status as a vet or paraveterinary professional.

Next, potential participants from each demographic were identified using a series of inclusion criteria. For the veterinary professional group, participants were required to be qualified in one of the roles detailed in Table 3.1, with no exclusion criteria implemented with respect to age, country of residence, or number of years of post-qualification experience. While some veterinary professionals also disclosed pet ownership, professional status was used as the overall criteria for assigning a demographic group. For the pet owner group, participants were required to own a dog or a cat at the time of participation. Once more, no exclusion criteria were implemented in relation to age, location, or level of experience.

While some Delphi consultation studies require expert respondents to have a minimum of three years of experience in their role (Rioja-Lang et al 2020a), this study aimed to collect and explore a broad spectrum of opinions, including those of newly qualified vets and first-time pet owners, meaning that no such experience-based criteria were implemented. Upon identifying potential participants, contact details were collated, involving a multi-step process, beginning with the creation of a contact database, to which details of known veterinary professionals within the United Kingdom and Australia were added. The active recruitment of participants was limited to the United Kingdom and Australia due to similarities in key aspects within the veterinary profession. For example, both countries have a national veterinary board (e.g., RCVS in the UK, AVBC in Australia) and both have national animal welfare regulation (Animal Welfare Act 2006 (UK) and the Animal Welfare Act 1999 (Australia)). In addition to this, Australia and UK veterinary professionals have similar views about the importance of aspects such as client communication and animal welfare (Hughes et al 2018). The RCVS Find a Vet Practice function was used to identify RCVS accredited small animal veterinary practices located in the United Kingdom. Practices with valid email addresses were identified and added to the contact database, noting the practice name and location. While an equivalent function could not be found on the Australian Veterinary Association webpage, an alternative strategy for identifying Australian veterinary practices was implemented. First, the Google search engine was used to list all cities in Australia, these were then grouped by state, and entered in turn, into the VetHelpDirect search function. Practices with valid email addresses were then identified and details were included in the contact database. The ACPAT find a physio function was then used to identify veterinary physiotherapists and hydrotherapists within the United Kingdom and Australia, with expertise in dogs and cats, before recording the details of all individuals with valid email addresses.

3.2.5 Discussion Board: Design

Due to social distancing measures imposed during the Coronavirus pandemic, an alternative to an in-person scoping meeting was required. As such, a digital forum, designed to enable anonymous conversation between expert participants, was designed.

Before the discussion board could be constructed, a landing page was created within the Asher Behaviour Lab website, hosted by the WordPress platform. The landing page highlighted the purpose and aims of the study, while describing a proposed novel device for use within veterinary healthcare (Appendix B). Additional features of the landing page included an in-built registration form, designed to collect demographic details of participants, including name, profession, country of residence and details of any experience surrounding the use of pet activity monitors. A final feature included an instructional video, which offered step-by-step instructions for interacting with the discussion board. The discussion board was then constructed using the Asgaros Forum plugin within the WordPress platform. To reduce the degree to which a disparity in experience would restrict interaction between participants, two separate discussion boards were created, the first of which would include pet owners, while the second would involve participation from veterinary professionals only. Within each discussion board, a summary of the Chordata device was posted, alongside a series of questions (Appendix C), which sought to present findings from the literature search, while encouraging participants to highlight and fill any remaining knowledge gaps.

3.2.6 Discussion board: recruitment

The inclusion criteria for participation in the discussion board matched those described in section 3.3.2. The recruitment of participants for each discussion board began by issuing an email including details of the study, as well as a link to the discussion board landing page, to all known veterinary professionals included in the contact database. As a snowball recruitment method was implemented, contacted individuals were asked to share information with any colleagues and friends that satisfied the target demographic. Recruitment materials (Appendix D) were then shared across social media platforms, including Twitter, Facebook, and Instagram, as well as LinkedIn. It was expected that at least two participants per demographic group would be recruited, and participation was incentivised with Amazon vouchers, whereby a £50 voucher was offered to the first 10 users to interact with the discussion board on two separate days.

3.2.7 Discussion board: response collection

Upon completion of the registration form, participants were allocated a non-identifiable username, and access to the relevant discussion board was granted. The discussion board remained active for two weeks, and responses were moderated daily. Once two weeks had elapsed, the discussion boards were closed, and responses were collated.

Responses from the theme 2 discussion board were added to the database created during the literature search, giving a comprehensive overview of parameters for consideration when diagnosing and monitoring canine osteoarthritis, as well as the technology required to measure such parameters. An additional database was then created, including responses from the theme 1 discussion board, including desirable features for novel technology, as well as any potential barriers to its implementation.

3.2.8 Questionnaire Design: Round One

Updated databases were used to develop questions for the digital questionnaire, which was constructed in three sections using Qualtrics survey software (Qualtrics 2022). The first section introduced the issue which the study sought to address, while also describing the novel device proposed by Chordata. Section two then collected demographic information including profession, contact details, and country of residence, before posing a series of 18 questions relating to the novel device (Appendix E), including the use of novel technology and its associated barriers, the importance of such technology within veterinary healthcare, and desirable user interface features for a novel device.

The third section of the survey included questions surrounding the diagnosis and monitoring of canine osteoarthritis (Appendix E), with a particular focus on priority gait parameters for measurement, and the technology required to do so. As with the discussion board, the content of the questionnaire was dependent upon the responses submitted to the demographic's questions, whereby sections one and two were visible to all participants, while access to section three was restricted to veterinary professionals.

Throughout sections two and three, a series of open and closed question formats were used. Multiple choice questions enabled users to select all relevant responses, while giving the opportunity to specify options that were not provided. Subsequent Likert scale questions then encouraged participants to rank the responses selected in previous questions, based upon a five-point scale. Closed questions largely sought 'yes/no', or 'agree/disagree' responses, while open questions allowed participants to share comments or elaborate on responses where required.

For closed and Likert scale questions, consensus was considered to be reached if agreement between participants reached or exceeded 75%. While the level of consensus selected throughout the literature can range from 50-97% (Nasa et al 2021), use of 75% aligns with other Delphi consultation studies in which animal welfare themes are addressed (Rioja-Lang et al 2020).

While a common stage in the Delphi consultation process involves pilot testing the designed questionnaire, to ensure that the structure and phrasing of questions is appropriate for participants, the low level of participation and engagement observed throughout the discussion board meant this stage of the process was not implemented.

3.2.9 Questionnaire Round one: Dissemination

A snowball recruitment method was used, whereby the survey and introductory materials were disseminated to all major veterinary practice groups, as well as a combined total of 500 veterinary practices and animal shelters across the UK and Australia, with a request for further dissemination to colleagues and friends who fulfilled the target demographic. Additional advertisement took place using a letter published in the Vet Record (Blake 2022), as well as posts made to social media platforms (including Facebook, Twitter, and Instagram, as well as LinkedIn) in addition to internal Newcastle University message boards and newsletters. The first round of the survey remained live for a duration of 19 weeks, after which time the questionnaire was closed, and responses (both complete and incomplete) were recorded and the level of agreement was calculated for each Likert scale question. The decision to include incomplete responses was made to maximise the amount of data collected in spite of low participation and high attrition rates. To allow for incomplete responses, analysis was conducted at the parameter level for each question, whereby the number of participants (raters) was recorded per parameter for each demographic group.

3.2.10 Questionnaire Round two: Refinement and redistribution

No additional rounds were required to satisfy the key theme presented by section 1 (use of technology), as overall agreement at the 75% consensus level was reached, whereby the level of consensus was determined by calculating the average agreement representative of all questions. Conversely, an additional round was required to address the theme posed by section 2 (parameters for OA detection). As such, the level of agreement reached for each section 2 question was calculated, identifying those which fell below the pre-defined level of 75%, before refining the questionnaire.

Refinement of the survey began by removing questions belonging to section 1. While this deviated from the routine Delphi process, section 1 sought to identify factors of importance when implementing novel technologies in veterinary therapeutics, with no additional requirement for such factors to be presented in a ranked order. Before modifying the format of all section 2 questions that did not reach consensus in the first round. When the phrasing of these questions remained the same, the number of possible options was collapsed from a five-point Likert scale to a binary response, i.e., important/not important. Next, questions that did reach consensus in the previous round were restructured to present the answers to each question in rank order of consensus level (beginning with the highest level of agreement) before asking participants whether they agreed/disagreed with the specified order, giving the opportunity to rearrange the order where required. Open questions were also posed, whereby participants were given the option to make any relevant comments or elaborate on responses submitted to previous questions.

The refined questionnaire (Appendix F) was then redistributed to all participants that provided a valid email address in the first round. The survey remained active for a duration of five weeks, after which time the survey closed and responses (both complete and incomplete) were recorded. The decision to include incomplete responses was made to maximise the amount of data collected in spite of low participation and high attrition rates. To allow for incomplete responses, analysis was conducted at the parameter level for each question, whereby the number of participants (raters) was recorded per parameter. The level of agreement was then calculated once more, using the previously described methods, and questions which reached consensus level were identified. For the remaining questions, it was considered that the observed level of agreement would not improve with the use of an additional questionnaire, and therefore no further survey rounds were required.

3.2.11 Data analysis: Questionnaire round one

Likert scale responses were first explored using descriptive statistics, whereby the rank sum and rank mean were calculated for each rated subject. Next, the Wilcoxon signed-rank test was used to highlight potential differences in opinions between the two stakeholder groups (veterinary professionals and pet owners). As the described statistics were used to identify difference in opinion at the individual parameter level, as opposed to question level, no correction for multiple testing was implemented, to avoid the introduction of type two error.

Within each demographic groups, the level of agreement for each question was also established. To do this, Likert scale responses were collapsed to a binary scale, whereby all possible responses were encompassed by one of two categories, for instance less important/important (Table 3.2).

Table 3.2. Example Likert scale responses and their corresponding categories when applying a binary approach.

	Category				
	Less Important		**Important**		
Response	Not at all important	Somewhat important	Important	Very important	Extremely important

Next, the percentage proportion of each category was calculated (Equation 3.1), and questions with a level of agreement equal to, or exceeding the pre-defined level of 75% were identified. Interrater reliability was then explored using Fleiss' Kappa statistics.

Equation 3.1. Percentage proportion. R= the number of each response, P=the number of participants

$$\% = \frac{\boldsymbol{R}}{\boldsymbol{P}} \times \mathbf{100}$$

Finally, thematic analysis was used to extract key themes from open questions posed in the first section of the questionnaire (Braun and Clarke 2006). To do this, data were first reviewed for each question, and any patterns in responses were identified. Next, topics were highlighted (for instance specified diseases or parameters), and their frequency was recorded throughout all responses collected per question. Topics that were recorded three or more times were considered to be a theme. While the described threshold is low, this was enforced due to the relatively low number of participants, whereby the implementation of a higher threshold may have resulted in key themes being missed. The frequency of each theme was then recorded, and quotes relating to each theme were extracted. This process was repeated separately for responses submitted by veterinary professionals and pet owners.

3.2.12 Data analysis: Questionnaire round two

The level of agreement was ascertained for each question, using percentage proportions and Fleiss Kappa statistics, as described in the previous section (3.2.11. Data analysis: Round 1). Descriptive statistics were used to establish the median position of each ranked parameter, as well as the variation surrounding this position.

3.3 Results

3.3.1 Discussion Board

Five veterinary surgeons participated in the discussion board, four of which were based in the United Kingdom, and one in Australia. No pet owners contributed to the discussion board.

Discussion board responses (Table 3.3 & Table 3.4) highlighted no withstanding knowledge gaps for theme 1. Despite this, additional methods for detecting and monitoring canine osteoarthritis, which were not extracted during the initial literature search were identified, these included: palpation, observation of muscle wastage, appreciation of myofascial trigger points, radiography, and observation of stance and posture.

Table 3.3 Summary of discussion board responses for questions surrounding the potential use of the proposed device, and the measurements this could make.

Question Summary	Response
Q1 – Measurable parameters using the proposed novel device	• Temperature and glucose noted as the two most useful parameters. Justification for this includes the fact that owners can easily miss signs of hypothermia in dogs and cats, while novel sensors could be used to avoid alternative, perhaps unpleasant methods of measurement. In addition to this, the measurement of glucose using the proposed novel sensor would avoid stress related to repeat blood sampling, particularly in diabetic cats. • Indicated that cortisol is not a useful standalone biomarker. • Noted that glucose monitoring may not be useful for individuals that are not diabetic. • Inactivity would be more useful than step count as this can vary for numerous reasons. • Aside from glucose and temperature, it would be useful if the device could monitor seizures, perhaps using activity and inactivity data.
Q2 – Likely audience for the proposed sensor	• Activity monitoring would be useful for physiotherapists and for monitoring orthopaedic problems, this would perhaps also be valuable for tailoring individual recommendations for activity, whereby the sensor could be purchased by owners or rented for a time from practices. • Based on the parameters recorded, vets may be best placed to interpret significance of information and decide on how best to proceed. • The potential for false alarms means it may not always be beneficial to alert for abnormalities. Alerts could however be useful for certain audiences such as ill, aged, or at-risk patients, including pregnant dogs, brachycephalics with heat stress, and diabetics.
Q3 - Use of the proposed sensor for the detection and long-term monitoring of osteoarthritis	• The most useful parameter would vary on a case-by-case basis (taking into consideration factors such as breed, age and affected joint etc), it’s unlikely that one single parameter would provide enough information to be of use. • It is possible that stride length could be affected in almost all joints affected by osteoarthritis, however, it would be necessary to know a normal stride length for the individual before identifying an alteration. • Step duration could be useful for identifying mild lameness. The use of joint kinematics could also eliminate tensing during range of movement physical exams in clinical settings.

Q4 - Integrating technology into veterinary practices	• It is unlikely that practices would invest in the proposed technology unless they had specialists. • Force platform selected as the technology which could most easily fit into practice, due to the potential for making measurements inexpensively, while identifying early stages of disease and monitoring response to treatment. • Microchips selected as technology which could most easily fit into practice as these appear to be the easiest to implant/implement and are perhaps the cheapest for owners to invest in, however uptake would be dependent on the socioeconomic status of clientele.
Q5 - Integrating technology into veterinary healthcare	• There is potential for clients to purchase the device. It could be of use to physiotherapists and in general practice for at risk patients. The abundance of information it would record could become problematic for practitioners when people question minor deviations. • Placement of the technology within the veterinary healthcare sector could depend on cost. At referral level, clients may be able to spend more. Within general practice it may be difficult to persuade clients to consider high-cost options. • Placement of technology would be best in specialist practices, as clients are usually not financially constrained, and expect a higher level of diagnostics, including the latest technology.
Q6 - Most common methods for detecting and monitoring canine osteoarthritis?	• Other: palpation, observation of muscle wastage, appreciation of myofascial trigger points, stance, and posture. • LOAD questionnaire, observation of mass and radiography (often declined by clients). • Other: Radiographs, however, these are only used for cruciate rupture. Radiographs are not used to diagnose just osteoarthritis.

Table 3.4 Summary of responses to discussion board questions surrounding the barriers to using the proposed sensor, and how these could be overcome.

Question summary	Response
Q1 – Most important barriers to use of the proposed sensor	• It is not uncommon to for patients to be intolerant of wearing devices. Additionally, clients may fail to follow instructions which may lead to destruction of the unit. Clients may also be averse to trying new technology if they believe their pet will not tolerate wearing it. • Practices are actively seeking ways for saving time; however, it is possible that they may not wish to invest time into initial learning and training on the devices. • Clients are typically concerned about cost when a new drug or technology is mentioned. • Sceptics may question what is wrong with using current methods of monitoring parameters, as these have been working all along, and can be treated with the drugs available. • If the device became global and as common as vaccinations or blood tests, it would give a lot of information, including population information. For now, however, it appears useful in research or in clinic research.
Q2 - Overcoming potential barriers to use of the proposed sensor	• Durability of the wearable component could overcome potential barriers. • Reassurance that the device wouldn't harm or hurt the animal.
Q3 – Desirable features of the user interface	• A design that is not complex
Q4 – Preferred forms of data presentation	• Visual presentation would be preferrable; however, a presentation option would be useful for people who process information in different ways. • Visual presentation of data would be useful for quick reference, with data also available in full if required. • Existing monitoring technology with effective data presentation include 'InfoVet', which is used in production animal practice, and draws graphs of parameters to highlight trends in the herd, such as mastitis and pregnancy rates. An additional technology is 'fence post', which measures individual milk production of cows, using graphs to highlight trends.
Q5 – Message interface between vets and clients	• A message interface may not be beneficial as there are already many platforms (clinic emails, texts, and marketing). For some, personal preference is to email clients with everything including prescriptions, handouts and invoices.
Q6 - Potential benefits to use	• There would be numerous potential benefits if the wearability and cost point were right.

of the proposed sensor	• For engaged clients who like visual data and evidence, the device could be beneficial, however most clients trust the recommendation of the vet, even if this is based on clinical suspicion as opposed to numbers. • The device will benefit monitoring and fine tuning of certain treatment and diagnosis (such as diabetes) however this is also based on the clinical picture.
Q7 - Client willingness to use the proposed sensor	• For ongoing monitoring of conditions (such as diabetes), the device would be particularly useful, however, not all clients would understand how to use the sensor, particularly when considering the estimated compliance for giving tablets. • The complexity of the device would not suit all clients. • Clients that are already doing yearly blood testing would be willing to use the device. • If the device was included in packages such as annual membership, uptake may be higher.
Q8 – Vet willingness to use the proposed sensor	• Vets may be unwilling to use the sensor due to a lack of applications that would translate to current specific practice. • Cardiologists may show interest if the device could measure resting respiratory rate. • For general monitoring of healthy patients, the device would be difficult to sell. • The device would be a useful option for the monitoring of sick patients; however, it may not be financially viable as an investment for this use.
Q9 – Could the proposed sensor benefit your knowledge of companion animals?	• The more data available for normal and diagnosed patients, the better the understanding of the diagnosis, however there is a current reliance for researchers to collect data and summarise the findings.

3.3.2 Questionnaire: Demographics

As both themes focussed on the implementation of technology, as opposed to development, researchers were not considered to be a required stakeholder group and were therefore not actively recruited for participation in the study. Despite this, responses received from researchers with experience of practicing as a veterinary professional were not excluded from the study, due to their overarching status as a vet or paraveterinary professional.

Most veterinary professionals were employed as veterinary surgeons in general practice with additional roles including veterinary nurses and veterinary surgeons in specialist/referral clinics (Table 3.5). Of the participants that specified their employment as ‘other’, specified roles included veterinary surgeons based in academia, charity/research and hydrotherapist.

Table 3.5. Roles of veterinary professionals, including roles specified after selecting 'other'.

Role	Total
Veterinary surgeon (general practice)	36
Veterinary nurse	6
Other	5
Veterinary physiotherapist	5
Veterinary surgeon (specialist/referral clinic)	5
Roles specified after selecting ‘other’	**Total**
Vet in academia	2
Hydrotherapist	1
Charity/research	1
Veterinary nurse/shelter manager	1

Participants were distributed across seven specified locations, and while most were based in the UK (41 individuals), five participants were based in the USA and Australia with a further two participants located in Germany. The remaining participants were distributed between France, Hong Kong and Malta, with one participant per location.

A total of 154 pet owners completed the demographics section of the questionnaire, however this number reduced to 91 participants that completed all survey questions. To maximise the amount of data collected, despite low participation and high rates of attrition, incomplete responses were included in analyses. To allow for this analysis was conducted at the parameter level for each question, whereby the number of participants (raters) was recorded per parameter for each demographic group.

Of the pet owners that participated in the questionnaire, dog owners formed the greatest proportion, followed by cat owners, and finally the owners of cats and dogs, with 83, 41, and 30 individuals respectively.

Participants were distributed across 13 specified locations, and while most were based in the UK, other locations included Germany and Australia (Table 3.6). Most pet owners did not have experience of using pet activity monitors, and only 17 participants indicated that they had used such devices with their own pets.

Table 3.6. Locations of dog/cat owners

Location	Total
United Kingdom	111
Australia	26
USA	3
France	2
Germany	2
Japan	2
Malaysia	2
Hungary	1
Latvia	1
Poland	1
South Africa	1
Thailand	1
The Netherlands	1

3.3.3 Questionnaire: Round one, theme one

Within each demographic group (veterinary professionals and pet owners), agreement was reached at a predefined level of 75% consensus regarding the most useful parameter measurable using the proposed sensor (table 3.7, Figure 3.4), however this parameter differed between the groups. While veterinary professionals considered glucose to be the most useful parameter, when ranked in order of agreement, pet owners regarded this to be cortisol. Conversely, step count was considered as the least useful parameter by veterinary professionals and pet owners, when ranked in order of agreement, with agreement for this parameter failing to reach consensus. Within each stakeholder group, a slight level of interrater reliability was observed in the ranking assigned to each parameter (Kappa <0.2, P <0.001) (Appendix G), a Wilcoxon signed rank test indicated a significant difference in the rank assigned to cortisol when comparing veterinary professionals and owners.

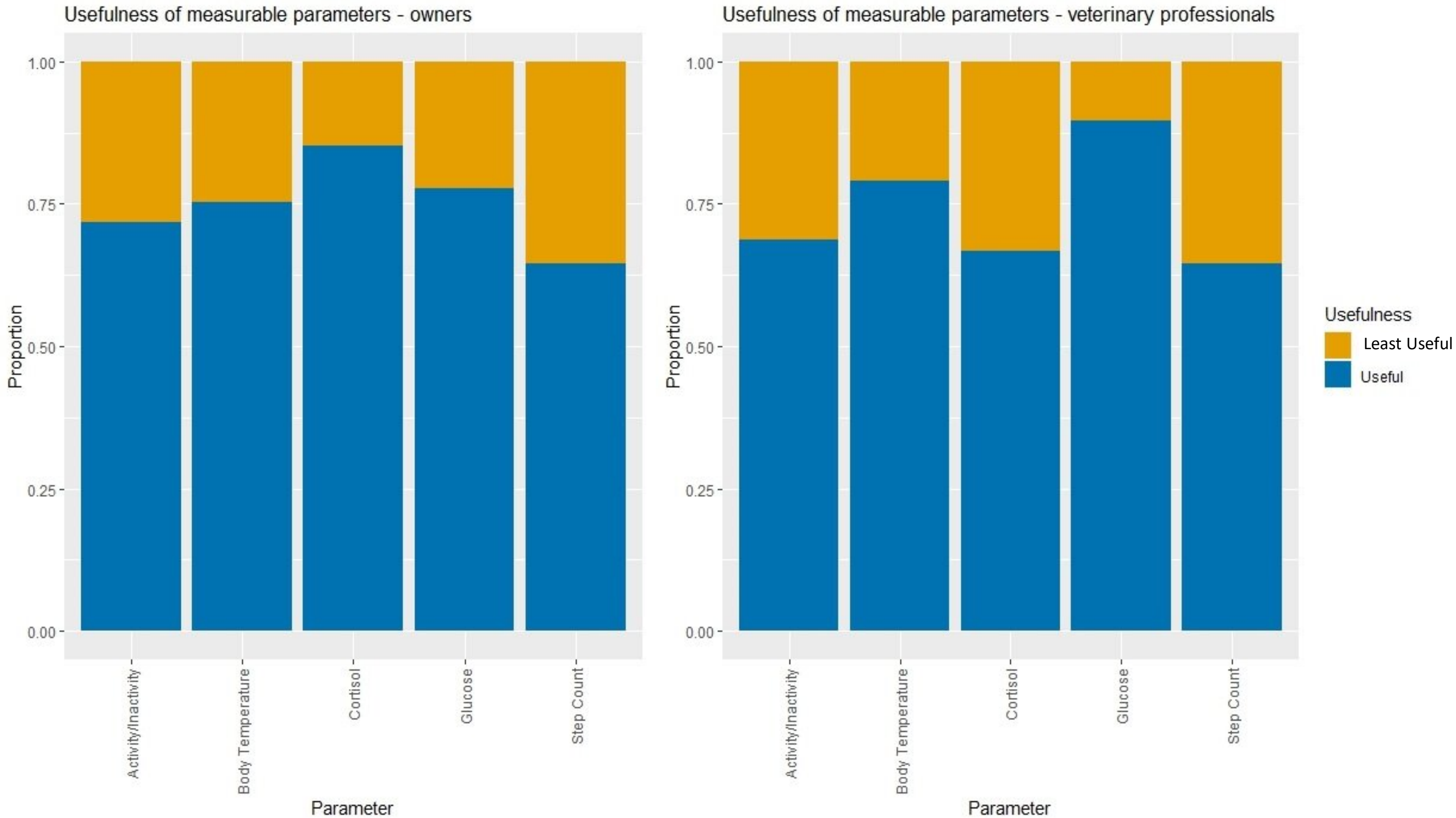


Figure 3.4. The perceived usefulness of measurable parameters, rated by owners and veterinary professionals. For a parameter to be considered useful or not useful, agreement between participants in each demographic group was required at a pre-defined level of 75% consensus.

Both veterinary professionals and pet owners suggested that the proposed device would be of most interest to veterinary physiotherapists (Table 3.7, Figure 3.5). Despite this, veterinary professionals predicted the device would be best placed in academic research settings and specialist referral practices, while pet owners believed the device would be most useful in paraveterinary settings, such as a physiotherapy clinic (Figure 3.6). In contrast, self-specified 'other' users, including veterinary researchers, and those responsible for managing complex cases, were predicted by veterinary professionals to be the least interested prospective user of the proposed device, with agreement for these users failing to reach consensus. Furthermore, non-clinical settings and self-specified locations including rescue centres were expected to be the least beneficial locations for the proposed device when ranked in order of agreement by vets and owners respectively. Consensus was reached for most users and locations, and the level of interrater reliability within each demographic was fair (kappa <0.4, $P <0.001$) (Appendix G), and no difference was noted when comparing the ranks assigned by vets and owners ($P >0.05$ across all Wilcoxon signed rank tests).

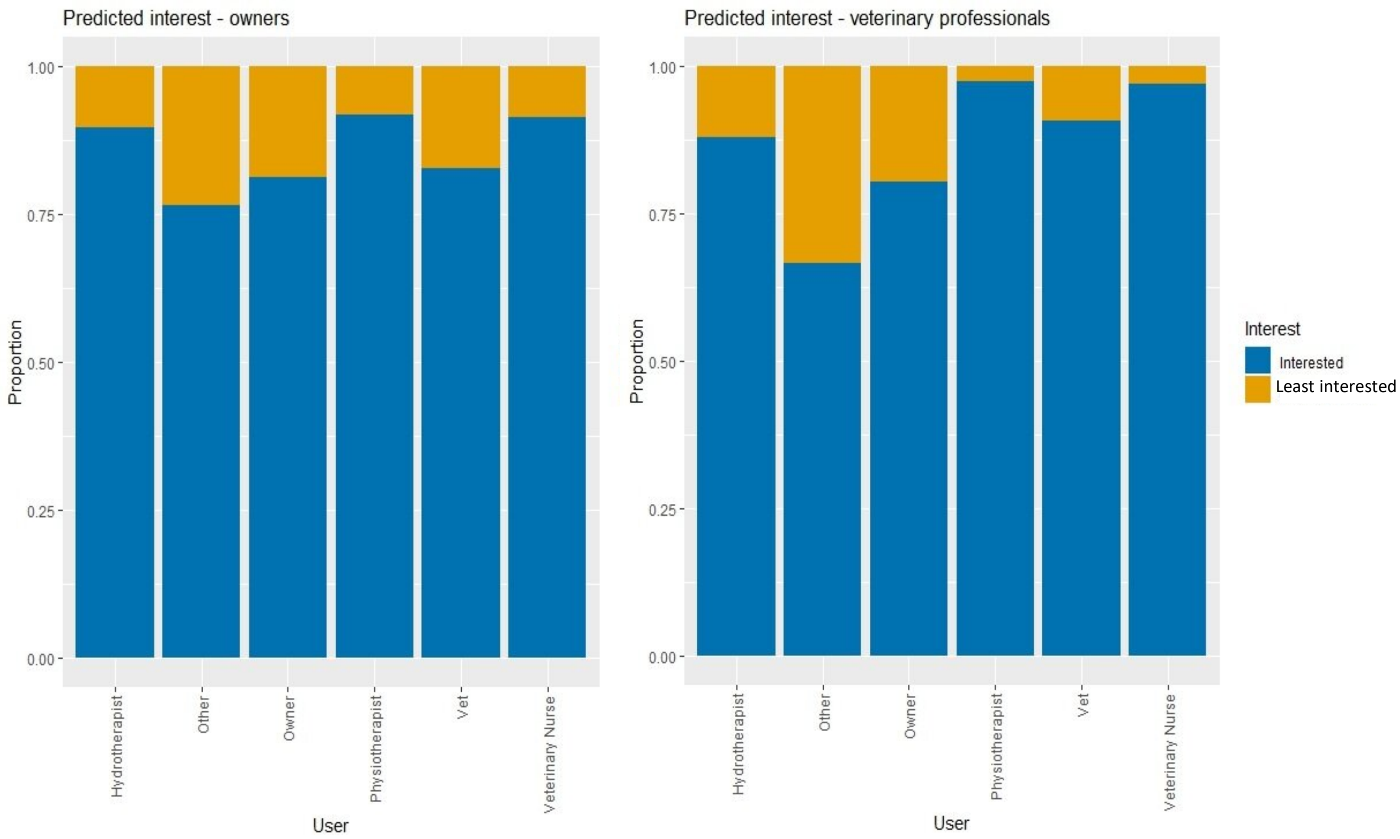


Figure 3.5. Predicted interest in the proposed device, rated by owners and veterinary professionals For a potential stakeholder to be considered interested or not interested, agreement between participants in each demographic group was required at a pre-defined level of 75% consensus

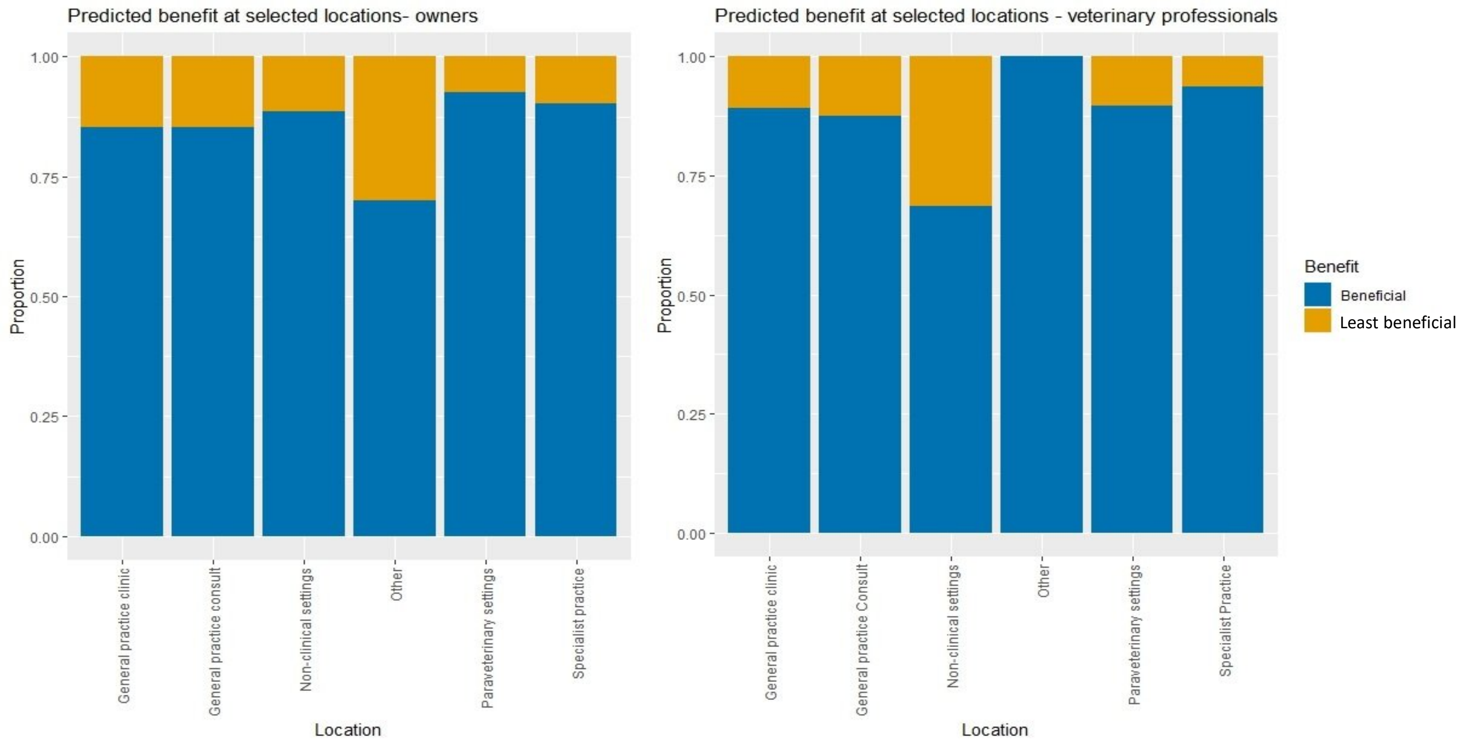


Figure 3.6 Predicted benefit of using the proposed sensor at the selected locations, rated by owners and veterinary professionals. For use of the sensor to be considered beneficial or not beneficial at a specified location, agreement between participants in each demographic group was required at a pre-defined level of 75% consensus

When considering potential benefits to use of the proposed sensor, veterinary professionals considered more effective clinical practice, and other self-specified options, including the management of complex cases, to be of highest importance based on level of agreement (Table 3.7, Figure 3.7). In contrast, the opportunity to implement telemedicine was considered the least important benefit among vets, with this option failing to reach consensus. While the importance of all potential benefits reached consensus among owners, easier communication was considered the most important, based on level of agreement. Consensus was reached for most benefits associated with using the proposed device, and the level of interrater reliability in the ranking of parameters within each demographic was fair (kappa <0.4, $P<0.001$) (Appendix G). Despite this, a Wilcoxon signed rank test indicated a significant difference in the rank assigned to easier communication and early detection of disease ($W=19116$ & 1885, $P=0.048$ & 0.035 respectively) when comparing the opinion of veterinary professionals and owners.

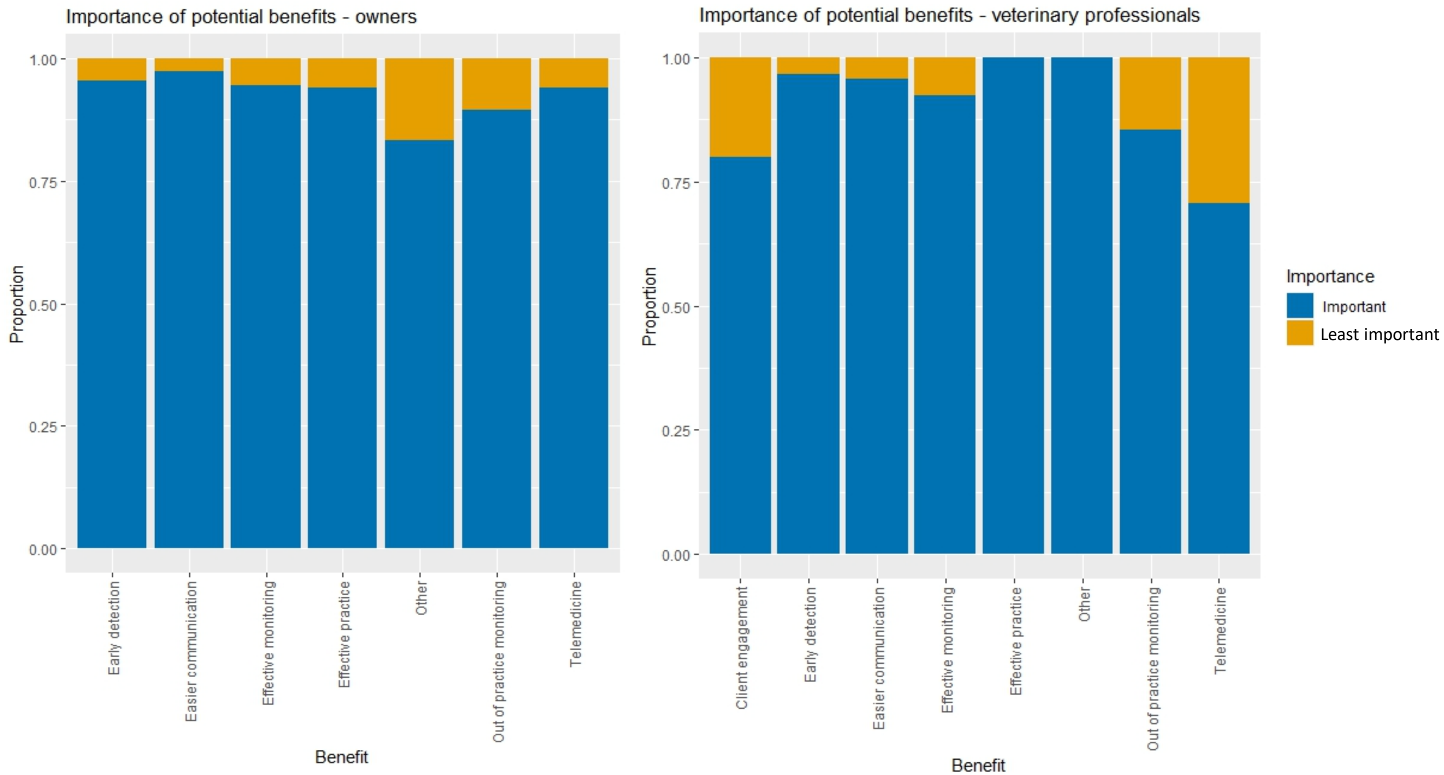


Figure 3.7. Perceived importance of benefits associated with using the proposed sensor, rated by pet owners and veterinary professionals. For a benefit to be considered important or not important, agreement between participants in each demographic group was required at a pre-defined level of 75% consensus

Each potential barrier to the use of the proposed sensor reached consensus for both veterinary professionals and pet owners (Table 3.7, Figure 3.8). Among veterinary professionals, the most important barriers, based on agreement, include legality of the device, time taken for use and training, integration potential, availability of the device, implantation of a second chip, and other self-specified barriers, including owner ability to understand and use the device, as well as data reliability. Conversely, owners considered the animals tolerance for wearing the device to be the most important barrier, based on level of agreement. Consensus was reached regarding the importance of each barrier, and the level of interrater reliability in the ranking of parameters within each demographic was fair (Kappa <0.4, P <0.001) (Appendix G) When comparing the two demographic groups, Wilcoxon rank tests highlighted differences in the rank assigned to the device complexity and availability, as well as the animal's tolerance for wearing this (W= 2788, 1835 and 1821, P=0.034, 0.019 and 0.024 respectively).

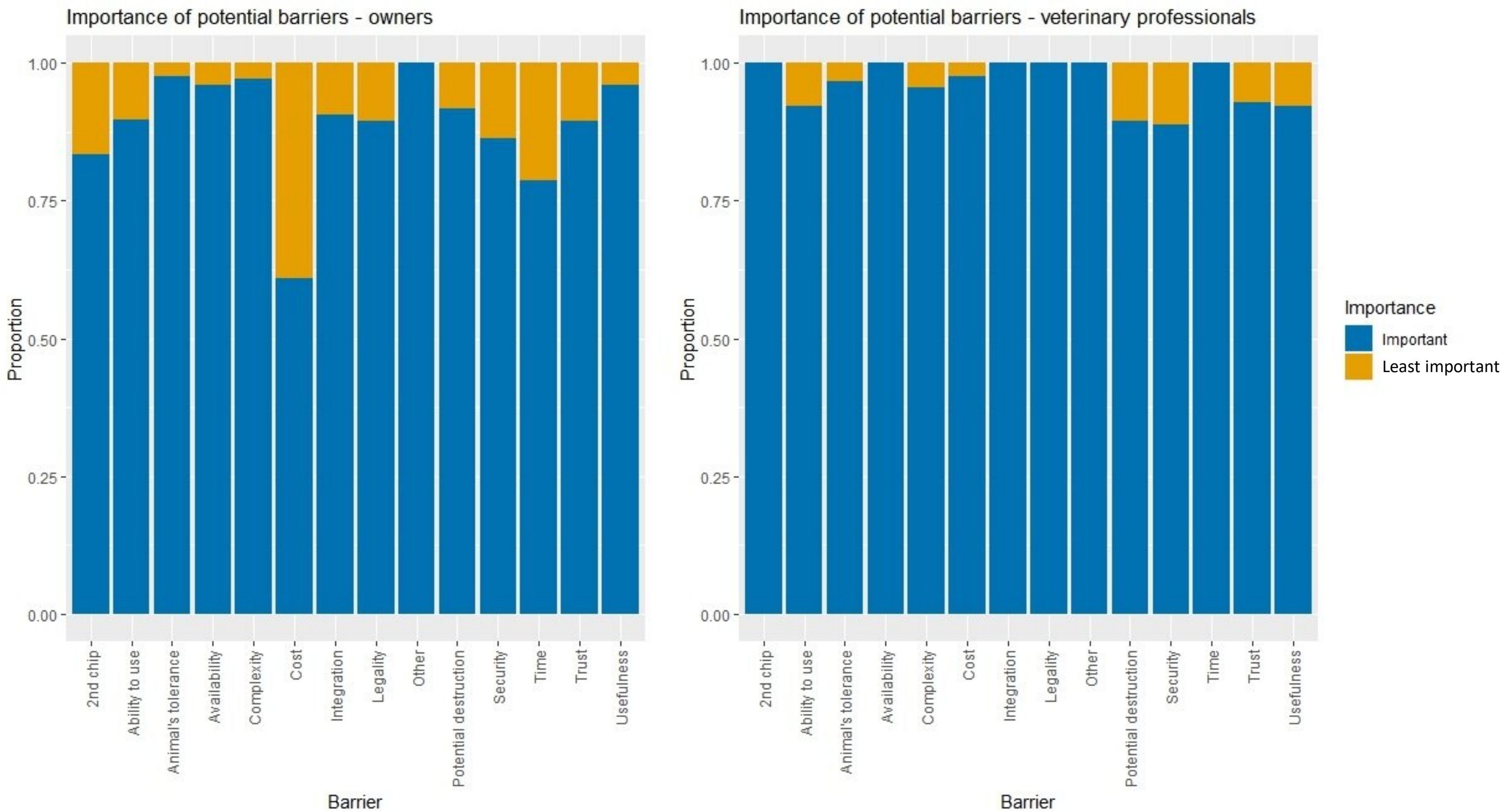


Figure 3.8 Perceived importance of potential barriers to using the proposed device, rated by pet owners and veterinary professionals. For a barrier to be considered important or not important, agreement between participants in each demographic group was required at a pre-defined level of 75% consensus

When considering potential solutions to the barriers associated with using the proposed device, consensus was reached for all options, for both veterinary professionals and pet owners (Table 3.7, Figure 3.9). While veterinary professionals ranked options including: causing no harm to the animal, interest of clients and durability, as well as self-specified options such as self-charging batteries among the most important based on agreement, pet owners prioritised self-specified options including the assurance of health benefits and peer review. Consensus was reached regarding the importance of each factor for overcoming potential barriers, and the level of interrater reliability in the ranking of parameters within each demographic was fair (Kappa <0.4, $P <0.001$) (Appendix G). When exploring responses from the two groups, a Wilcoxon rank test indicated differences in importance assigned to causing no harm to the animal ($W=1429$, $P <0.01$).

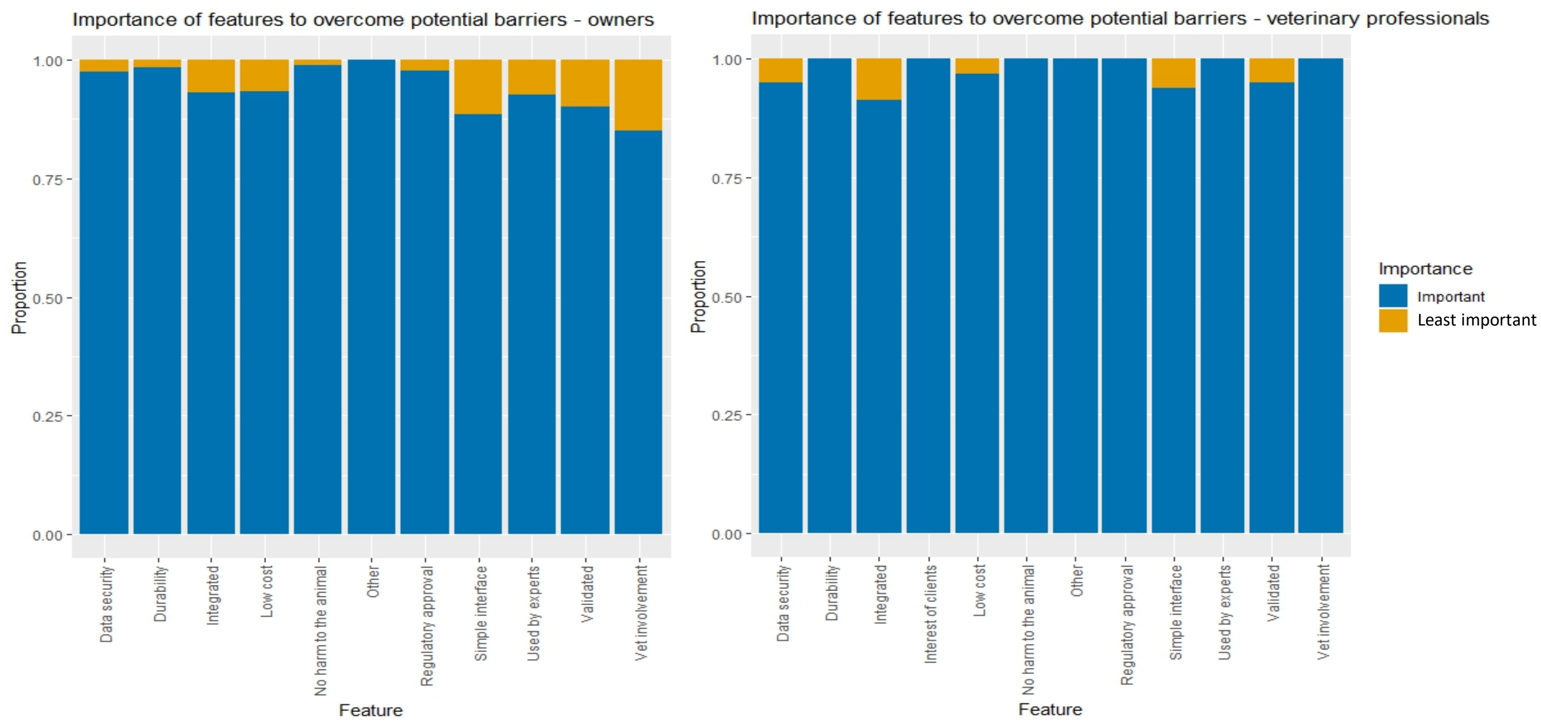


Figure 3.9 Perceived importance of features for overcoming potential barriers to using the proposed device, rated by pet owners and veterinary professionals. For a feature to be considered important or not important, agreement between participants in each demographic group was required at a pre-defined level of 75% consensus

All potential interface features for the proposed device were considered to be important by both pet owners and veterinary professionals (Table 3.7, Figure 3.10), with agreement for all features exceeding the pre-defined level of 75%, despite this, interrater agreement within each demographic remained fair (kappa <0.4, $P <0.001$) (Appendix G). Veterinary professionals placed most importance on features such as the capacity for updates, undo and redo options, visibility of system status and a message interface, while a self-defined option assigned high importance to the extra work associated with a message interface. While owners also considered the visibility of system status with high importance, based on level of agreement, other features included responsiveness and the inclusion of varying skill levels, as well as self-specified options including access to technical support and data anonymity. When comparing the responses of veterinary professionals and pet owners, a Wilcoxon signed rank test highlighted differences in the importance assigned to system status visibility and the inclusion of a message interface ($W = 1679$ and 1660.5, $P = 0.04$ and 0.046 respectively).

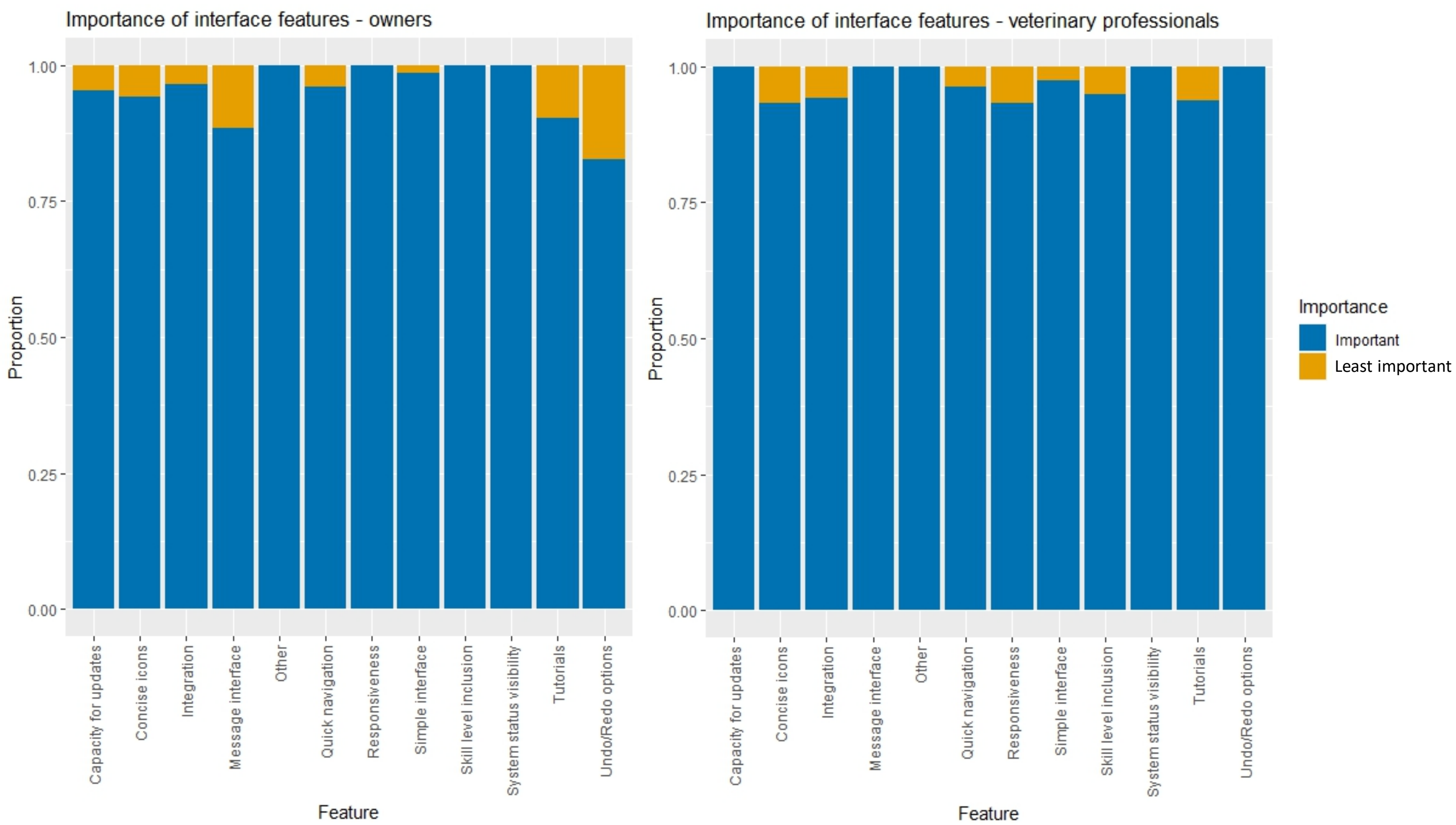


Figure 3.10. Perceived importance of interface features for the proposed device, rated by pet owners and veterinary professionals. For a feature to be considered important or not important, agreement between participants in each demographic group was required at a pre-defined level of 75% consensus

When considering the convenience of data presentation formats implemented by the prospective device, both veterinary professionals and pet owners failed to reach consensus regarding the use of raw data (Table 3.7, Figure 3.11). Consensus was reached for all remaining data presentation formats, and interrater agreement was fair within each demographic group (Kappa <0.4, P <0.001) (Appendix G). Although both veterinary professionals and pet owners considered graphs to be the most convenient data presentation format, based on level of consensus, a Wilcoxon signed rank test highlighted differences in the ranked convenience of text as a data presentation format (W =1564, P=0.033).

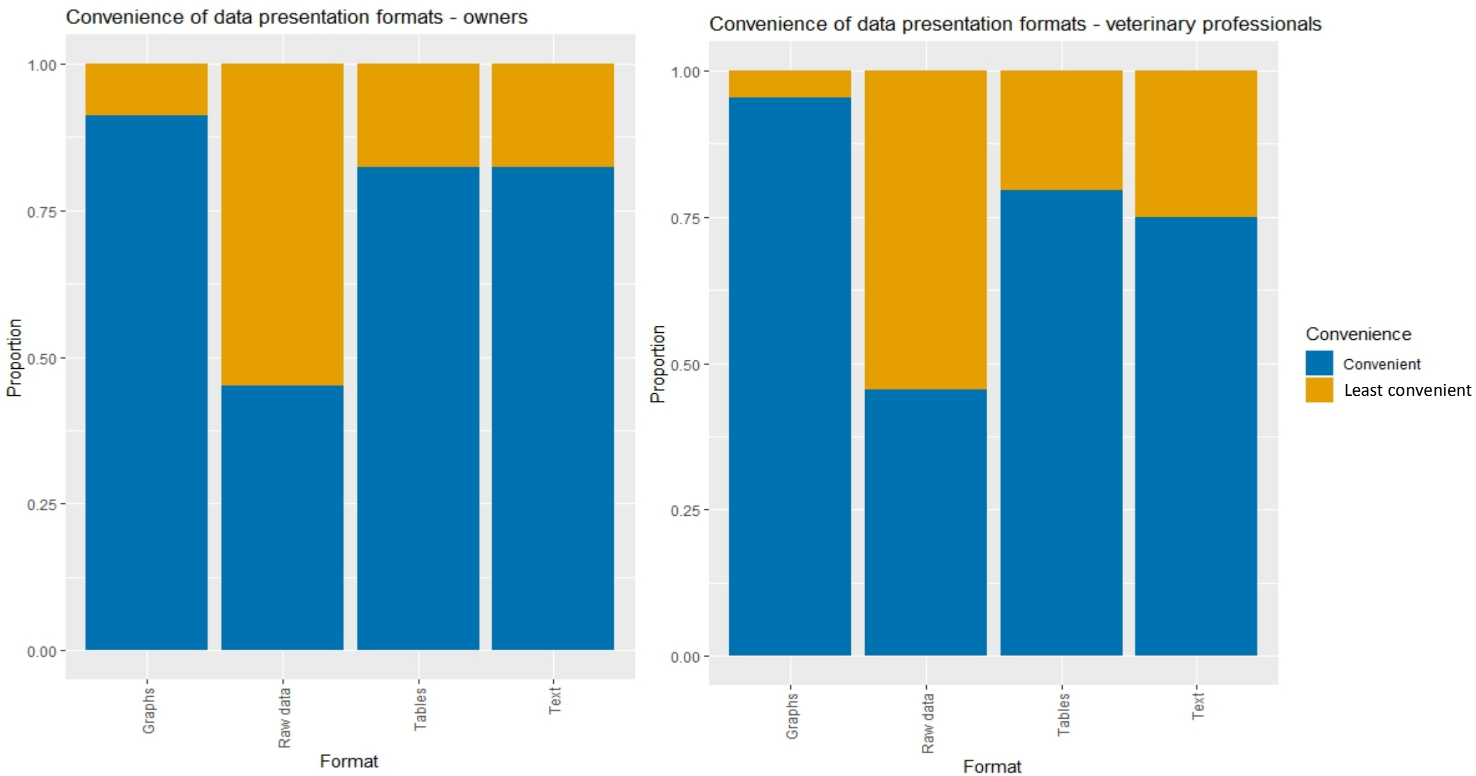


Figure 3.11. Perceived convenience of data presentation formats for the proposed sensor, rated by pet owners and veterinary professionals. For a format to be considered convenient or not convenient, agreement between participants in each demographic group was required at a pre-defined level of 75% consensus

Table 3.7. Summary of agreement, descriptive statistics, and Wilcoxon test statistics for round one, theme one questionnaire responses. Wilcoxon tests were used to compare the opinion of vets and owners, with significance indicating divergence in opinion between the two stakeholders. The agreement reached column indicates parameters for which agreement within stakeholder groups reached consensus at the pre-defined level (75%). For each stakeholder group (vets and owners), the highest ranked parameter (based on percentage agreement) is emboldened and highlighted in grey. For instances in which multiple parameters shared the same percentage agreement, each parameter was marked with an asterisk (*) in the agreement column, and rank was established based on the highest rank mean.

Question	Parameter	Significant	Agreement Reached	Participant	Number of participants	Agreement	Rank mean	W Value	P Value
1	**Glucose**	✗	✓	**Vet**	**48**	**90%**	**3.46**	**3411**	**0.056**
			✓	Owner	121	78%	3.17		
	Cortisol	✓	✗	Vet	48	67%	2.92	**1946**	**0.000**
			✓	**Owner**	**121**	**85%**	**3.45**		
	Body temperature	✗	✓	Vet	48	79%	3.21	3042	0.609
			✓	Owner	121	75%	3.11		
	Step Count	✗	✗	Vet	48	65%	2.79	2874	0.912
			✗	Owner	121	64%	2.79		
	Activity	✗	✗	Vet	48	69%	2.98	2789	0.672
			✗	Owner	121	72%	3.00		
3	Hydrotherapist	✗	✓	Vet	25	88%	3.48	3239	0.166
			✓	Owner	68	90%	3.75		
	Other	✗	✗	Vet	3	67%	3.00	2968	0.683
			✓	Owner	17	76%	3.59		
	Owner	✗	✓	Vet	41	80%	3.44	2927	0.797
			✓	Owner	101	81%	3.57		
	Physiotherapist	✗	✓	Vet	38	97%	3.79	**2566**	**0.279**
			✓	**Owner**	**86**	**92%**	**3.87**		
	Vet	✗	✓	**Vet**	**43**	**91%**	**3.88**	**2705**	**0.585**
			✓	Owner	99	83%	3.68		

	Veterinary Nurse	✗	✓	Vet	34	97%	3.88	2618	0.135
			✓	Owner	82	91%	3.79		
5	General Practice Consultation	✗	✓	Vet	32	88%	3.69	2833	0.512
			✓	Owner	68	85%	3.63		
	General Practice Clinic	✗	✓	Vet	28	89%	3.79	2928	0.291
			✓	Owner	54	85%	3.74		
	Specialist Practice	✗	✓	Vet	32	94%	3.91	2919	0.315
			✓	Owner	61	90%	3.97		
	Paraveterinary Setting	✗	✓	Vet	29	90%	3.72	**2616**	**0.851**
			✓	**Owner**	**68**	**93%**	**3.78**		
	Non-clinical Setting	✗	✗	Vet	24	69%	4.54	2520	0.579
			✓	Owner	70	89%	3.70		
	Other	✗	✓	**Vet**	**1**	**100%**	**5.00**	**2484**	**0.125**
			✗	Owner	10	70%	3.20		
7	**Easier Communication**	✓	✓	Vet	24	96%	4.00	**1916**	**0.048**
			✓	**Owner**	**77**	**97%**	**4.03**		
	Early Detection of disease	✓	✓	Vet	30	97%	4.13	1885	0.035
			✓	Owner	88	95%	4.23		
	Effective condition Monitoring	✗	✓	Vet	39	92%	4.15	2352	0.890
			✓	Owner	91	95%	4.19		
	Out of Practice Monitoring	✗	✓	Vet	41	85%	3.63	2397	0.963

			✓	Owner	86	90%	3.85		
	Telemedicine	✗	✗	Vet	17	71%	2.94	2415	0.888
			✓	Owner	33	94%	3.70		
	Effective Practice	✗	✓	Vet	16	**100% ***	4.13	2154	0.298
			✓	Owner	50	94%	3.92		
	Client Engagement	✗	✓	Vet	20	80%	3.40	NA	NA
			✗	Owner	0	NA	NA		
	Other	✗	✓	**Vet**	**1**	**100%**	**5.00**	**2306**	**0.378**
			✓	Owner	6	83%	3.33		
9	Cost	✗	✓	Vet	40	98%	4.18	2400	0.795
			✓	Owner	92	97%	4.13		
	Legality	✗	✓	**Vet**	**4**	**100%**	**4.25**	**2124**	**0.155**
			✓	Owner	19	89%	4.05		
	Time	✗	✓	Vet	15	**100% ***	4.00	2458	0.559
			✓	Owner	33	79%	3.42		
	Ability to Use	✗	✓	Vet	13	92%	3.62	2379	0.841
			✓	Owner	29	90%	3.45		
	Usefulness	✗	✓	Vet	13	92%	3.92	2445	0.574
			✓	Owner	25	96%	4.12		
	Complexity	✓	✓	Vet	23	96	3.74	2788	0.034
			✓	Owner	34	97%	3.71		
	Integration	✗	✓	Vet	12	**100% ***	3.58	2223	0.549
			✓	Owner	32	91%	3.75		
	Availability	✓	✓	Vet	12	**100% ***	3.67	1835	0.019
			✓	Owner	49	96%	3.80		

	Trust	✕	✓	Vet	14	93%	3.93	2668	0.063
			✓	Owner	19	89%	3.58		
	2nd_chip	✕	✓	Vet	24	**100% ***	3.75	2547	0.355
			✓	Owner	48	83%	3.58		
	Security	✕	✓	Vet	9	89%	3.67	2293	0.786
			✓	Owner	22	86%	4.05		
	Animals Tolerance	✓	✓	Vet	30	97%	4.17	1821	0.024
			✓	Owner	81	98%	4.43		
	Potential Destruction	✕	✓	Vet	19	89%	3.84	2231	0.622
			✓	Owner	49	92%	3.84		
	Other	✕	✓	Vet	6	**100% ***	4.00	**2509**	**0.140**
			✓	**Owner**	**6**	**100%**	**4.67**		
11	Validated	✕	✓	Vet	39	95%	3.92	2198	0.946
			✓	Owner	81	90%	3.96		
	Integrated	✕	✓	Vet	23	91%	3.52	2180	0.992
			✓	Owner	44	93%	3.91		
	Interest of Clients	✕	✓	Vet	24	**100%***	4.08	NA	NA
			✓	Owner	0	NA	NA		
	Vet Involvement in development	✕	✓	Vet	15	**100%***	3.53	1779	0.050
			✓	Owner	47	85%	3.79		
	Data Security	✕	✓	Vet	20	95%	3.75	2166	0.938
			✓	Owner	40	98%	4.10		
	Simple interface	✕	✓	Vet	32	94%	3.69	2447	0.227

			✔	Owner	52	88%	3.88		
	Low Cost	✖	✔	Vet	30	97%	3.70	2094	0.685
			✔	Owner	60	93%	3.98		
	Used by Experts	✖	✔	Vet	14	**100%***	3.71	1874	0.122
			✔	Owner	41	93%	4.00		
	Regulatory Approval	✖	✔	Vet	18	**100%***	3.56	1845	0.100
			✔	Owner	44	98%	4.45		
	Causes no Harm to The Animal	✔	✔	Vet	29	**100%***	4.52	1429	0.000
			✔	Owner	87	99%	4.71		
	Durability	✖	✔	Vet	28	**100%***	4.07	2127	0.802
			✔	Owner	65	98%	3.97		
	Other	✖	✔	**Vet**	**1**	**100%**	**5.00**	**2120**	**0.432**
			✔	**Owner**	**5**	**100%**	**4.60**		
13	**Simple Interface**	✖	✔	Vet	38	97%	4.24	2252	0.324
			✔	Owner	74	99%	4.18		
	Quick Navigation	✖	✔	Vet	27	96%	4.04	2339	0.154
			✔	Owner	51	96%	3.71		
	Concise Icons	✖	✔	Vet	15	93%	3.67	1951	0.612
			✔	Owner	35	94%	3.77		
	Responsiveness	✖	✔	Vet	30	93%	3.80	2287	0.245
			✔	Owner	52	**100%***	3.85		
	Integration	✖	✔	Vet	17	94%	3.65	2122	0.680
			✔	Owner	29	97%	4.14		
		✖	✔	Vet	17	**100%***	3.82	1830	0.273

	Capacity For Updates		✓	Owner	44	95%	3.95		
	Undo and Redo Options	✕	✓	Vet	12	**100%***	3.75	2096	0.766
			✓	Owner	23	83%	3.70		
	System Status Visibility	✓	✓	Vet	9	**100%***	3.78	1679	0.040
			✓	Owner	35	**100%***	3.91		
	Inclusion of Varying Skill Levels	✕	✓	Vet	20	95%	4.05	**2185**	**0.475**
			✓	**Owner**	**38**	**100%**	**3.97**		
	Tutorials	✕	✓	Vet	16	94%	3.75	1838	0.283
			✓	Owner	41	90%	3.98		
	Inclusion of a Message Interface	✓	✓	Vet	13	**100%***	3.77	1661	0.046
			✓	Owner	43	88%	3.98		
	Other	✕	✓	**Vet**	**1**	**100%**	**5.00**	**1984**	**0.420**
			✓	Owner	5	100%	4.60		
14	**Graphs**	✕	✓	**Vet**	**44**	**95%**	**3.84**	**2149**	**0.470**
			✓	**Owner**	**91**	**91%**	**3.71**		
	Tables	✕	✓	Vet	44	80%	3.27	1933	0.734
			✓	Owner	91	82%	3.36		
	Text	✓	✕	Vet	44	75%	3.18	1564	0.033
			✓	Owner	91	82%	3.63		
	Raw Data	✕	✓	Vet	44	54%	2.41	1880	0.553
			✓	Owner	91	54%	2.56		

Of the 44 vets that completed all questions relating to theme 1, 38 agreed that the proposed device could support them in the diagnosis, treatment, and monitoring of health conditions in dogs and cats, while the six remaining veterinary professionals indicated that they were not sure. Similarly, a of the 91 animal owners that completed all theme 1 questions, 75 believed that the device could support them in the identification and management of health conditions in their own pet, while three pet owners disagreed with the statement. The 13 remaining pet owners were not sure.

When asked to elaborate on the ways in which the proposed device could support the diagnosis, treatment and management of health conditions, a total of 10 themes were extracted from the responses of veterinary professionals. Of the identified themes, 'diabetes' was discussed most frequently, followed by 'management and monitoring', with references made in 20 and 16 responses respectively (Table 3.8). Meanwhile, less common themes included 'out of practice monitoring' and 'Addisons', each featuring in two responses.

Pet owners were also asked to comment on the ways in which the proposed device could support the identification and management of health conditions in their dog or cat. A total of 15 key themes were identified from the submitted responses, whereby 'management/monitoring' was discussed most frequently. Followed by 'early detection' and 'diagnosis/identification', with references made in 35, 22 and 15 responses respectively, from a total of 91 responses (Table 3.8). Conversely, less common themes included 'communication', 'out of practice monitoring' and 'Cushings', with references made in three, three and two responses respectively.

Most veterinary professionals and pet owners believed the device could benefit the relationship between the two stakeholders (31 and 61 individuals respectively), however six pet owners and one veterinary professional disagreed with this statement, with the remaining veterinary professionals and pet owners (12 and 23 respectively) stating they were not sure. When asked how the proposed device could support the relationship between pet owners and vets, veterinary professionals discussed a total of eight key themes. Of these, 'conversation/communication' was mentioned most frequently, followed by 'data' and trust', with references made in 10, eight and five responses respectively (Table 3.8a). Meanwhile, less common themes included 'owner control' and 'stress'.

When considering owner responses to the same question, nine key themes were identified, of which, 'data' was discussed most frequently, followed by 'conversation/communication' and ‘owner control’, with references made in 26, 23 and 12 responses respectively (Table 3.8a). Conversely, less common themes included ‘out of practice monitoring’ and ‘stress’, which were referenced in five and three responses respectively.

A majority of veterinary professionals and pet owners suggested that they would be willing to use the proposed device if this was validated, with regulatory approval (34 and 52 individuals respectively). Despite this, a substantial proportion of participants including 9 veterinary professionals and 35 pet owners, stated their use of the device would depend on additional factors, including cost, ease of use, and trust, both in the device and in the data this produced. Remaining veterinary professionals and pet owners confirmed they would not be willing to use the proposed device (1 and 3 participants respectively).

Participants that stated their use of the device would depend on additional factors were prompted for additional information. Responses from veterinary professionals consisted of three themes, including trust, functionality and cost (Table 3.8). Meanwhile, dog and cat owners raised seven themes, of which, tolerance was discussed most frequently, followed by cost and medical status, with references made in eight, seven and six responses respectively (Tables 3.8, 3.8a and 3.8b). Less common themes included safety and the need for more information, with two and three responses respectively.

Table 3.8. Key themes raised by veterinary professionals, as well as dog and cat owners, when discussing ways in which the proposed device could support the diagnosis, treatment and management of conditions in companion animals.

Veterinary Professionals		
Theme	**Total**	**Notes**
Diabetes	20	This condition could be diagnosed and monitored using glucose, body temperature and change in habits
Management/monitoring	16	-
Osteoarthritis /Degenerative joint disease	9	Diagnosis/monitoring using activity
Activity	6	-
Cushings	6	Diagnosis/monitoring using glucose, body temperature and change in habits
Early detection	6	-
Stress	6	-
Communication	3	-
Addisons	2	Diagnosis/monitoring using glucose, body temperature and change in habits
Out of Practice monitoring	2	-
Pet Owners		
Theme	**Total**	**Notes**
Management/monitoring	35	-
Early detection	22	-
Diagnosis/identification	15	-
Activity	9	-
Stress	9	-
Age	8	-
Data	8	-
Behaviour	6	-
Osteoarthritis/Degenerative joint disease	6	These conditions could be monitored by measuring glucose, cortisol, temperature, pain, and monitoring effects of day/weather/year/heat/cold

Diabetes	5	This condition could be diagnosed and monitored using activity levels, glucose and weight management
Reassurance	4	-
Unnecessary visits	4	-
Communication	3	-
Out of practice	3	-
Cushings	2	This condition could be diagnosed and monitored using activity levels, glucose, and weight management

Table 3.8a. Key themes raised by veterinary professionals, as well as dog and cat owners, when discussing ways in which the device could support the relationship between vets and owners.

Veterinary Professionals		
Theme	**Total**	**Notes**
Conversation/communication	10	Potential issues regarding sensitivity of the device
Data	8	-
Trust	5	-
Collaboration	4	-
Management/monitoring	4	Joint management and activity
Out of practice monitoring	4	-
Owner control	3	-
Stress	3	-
Pet Owners		
Theme	**Total**	**Notes**
Data	26	-
Conversation/communication	23	-
Owner control	12	-
Management/monitoring	11	-
Support diagnosis	11	-
Collaboration	8	-
Trust	7	No costs or hidden fees
Out of practice monitoring	5	-
Stress	3	-

Table 3.8b. Key themes raised by veterinary professionals, as well as dog and cat owners, when discussing factors influencing willingness to use the proposed device.

Veterinary Professionals		
Theme	**Total**	**Notes**
Trust	4	Indication that veterinary professionals would wait for others to try the sensor first.
		Concerns regarding potential abuse of the systems.
Functionality	3	Concerns regarding size and weight of the sensor, as well as the need for wearing a collar.
		Functionality of the device in a shelter setting.
Cost	2	Concerns regarding the willingness of clinics to invest.
Pet owners		
Theme	**Total**	**Notes**
Animal's tolerance	8	-
Cost	7	Concerns regarding false positives, causing exploratory intervention.
Medical status	6	Indication that the device would be used if the animal had a medical condition that required monitoring.
Ease of use/practicality	3	Practicality concerns for animals that don't wear collars.
More information needed	3	Indication that the device would be used with vet recommendations. Concerns regarding data sharing with insurance companies.
Wait until more widely used	3	-
Safety	2	-

3.3.4 Questionnaire: Round one, theme two

Theme two of the questionnaire accepted responses from veterinary professionals only. While 42 participants completed the first question, attrition occurred throughout the section, reducing the number of participants to 34 veterinary professionals that completed the section in its entirety. To maximise the amount of data collected, despite low participation and high rates of attrition, incomplete responses were included in analyses. To allow for this analysis was conducted at the parameter level for each question, whereby the number of participants (raters) was recorded per parameter.

Participating veterinary professionals were unable to reach consensus regarding how they perceived pet owner understanding of canine osteoarthritis. While 11 participants rated this understanding as good or very good, 31 participants considered this to be average, poor, or very poor. Despite this, consensus regarding the perceived ability of owners to recognise symptoms of osteoarthritis did reach consensus, whereby 32 participants rated owner ability as average, poor, or very poor, while the remaining 9 participants rated this as very good or good.

All proposed methods of diagnosing canine osteoarthritis were considered useful, with agreement reaching the predefined level of consensus (Table 3.9, Figure 3.12), and a fair level of interrater reliability (kappa = 0.113) (Table 3.10). Of the suggested methods, appreciation of myofascial trigger points and palpation were considered most useful, based on level of consensus. Conversely, the lowest levels of consensus were associated with, use of the LOAD questionnaire, probing questions, and owner description of symptoms. When considering the practicality of the proposed methods, use of the LOAD questionnaire and appreciation of myofascial trigger points were among the most practical, when ranked based on the level of consensus. All remaining methods were also considered to be practical, and the level of interrater agreement remained fair (Kappa = 0.106). The lowest levels of consensus were associated with the use of radiography, probing questions, and the owner's description of symptoms.

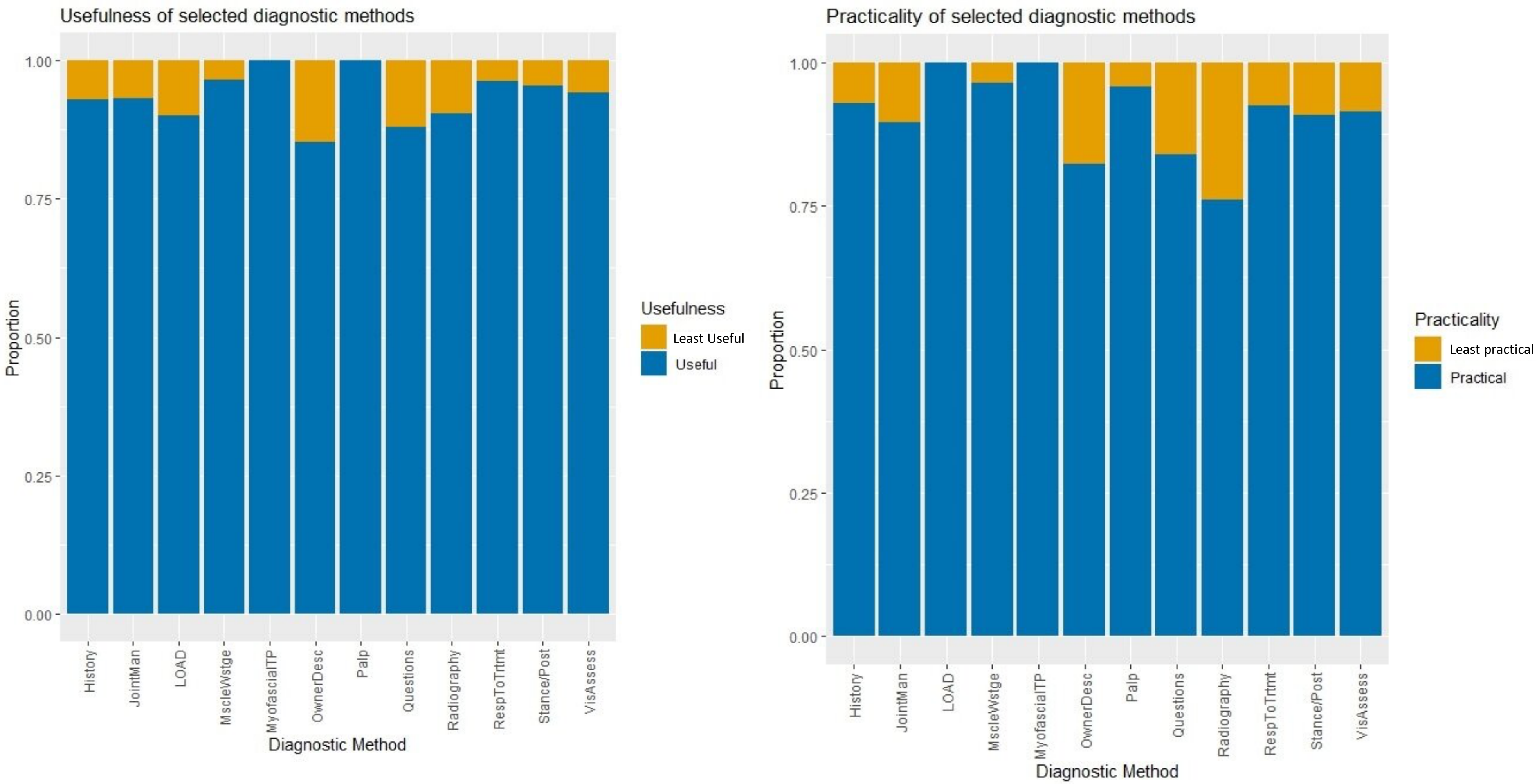
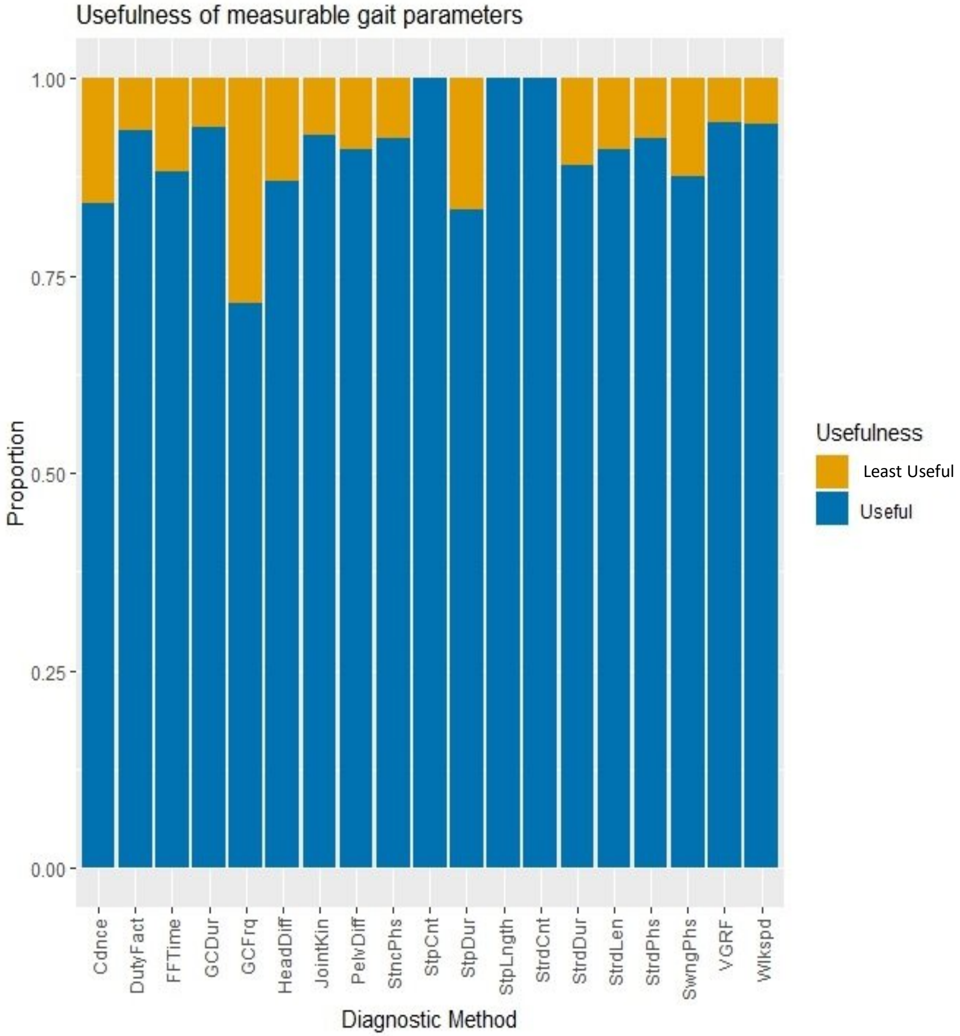


Figure 3.12 Usefulness and practicality of selected diagnostic methods, rated by veterinary professionals

Veterinary professionals reached consensus regarding the usefulness of 18 gait parameters which could be measured for detecting and monitoring the early stages of canine osteoarthritis, with agreement for just one gait parameter, gait cycle frequency, falling below the pre-defined level of consensus (Figure 3.13). Agreement between raters was fair (Kappa=0.106). Of the parameters that reached consensus, step count, step length and stride count were regarded as the most useful, based on level of agreement. Interrater agreement remained fair when considering the practicality associated with measuring the selected gait parameters (Kappa >0.4), whereby veterinary professionals failed to reach consensus regarding the practicality of nine of the presented parameters. The least practical parameters, based on level of consensus, included stance phase and gait cycle frequency. Conversely, the parameters considered most practical for measurement, based on level of agreement, included step count, walking speed and stride count



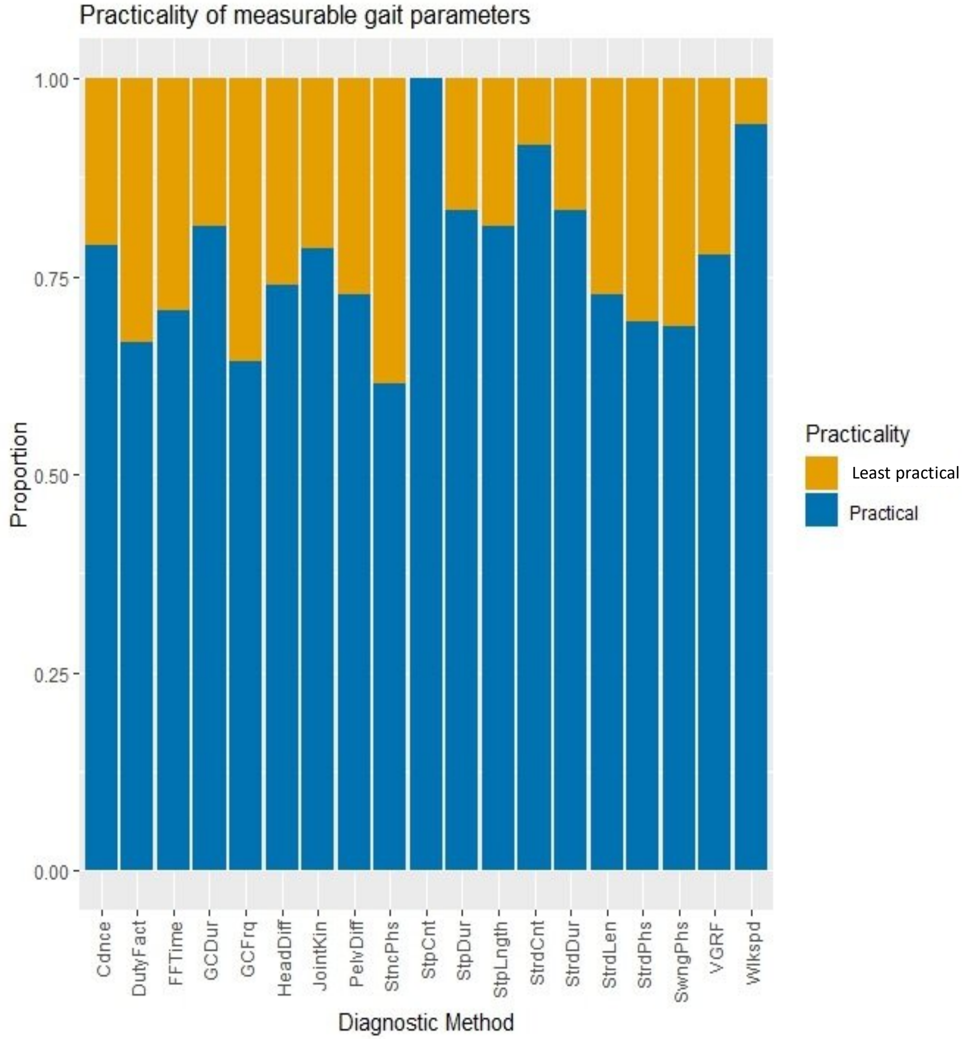


Figure 3.13 Usefulness and practicality of measurable gait parameters, rated by veterinary professionals

When considering the equipment required to measure gait parameters, veterinary professionals achieved consensus regarding the usefulness of all five options (Figure 3.14), despite this, interrater agreement was slight (Kappa <0.1). When ranked based on level of agreement, X-Ray and high-speed cameras were considered the most useful technology for detecting and monitoring the early stages of canine osteoarthritis, followed by motion capture. When considering the practicality of the presented technology, interrater agreement remained slight (Kappa <0.1, and the use of X-Ray was the only option to reach consensus. Of the remaining technology, the use of sensors was considered the least practical, based on level of consensus, followed by motion capture.

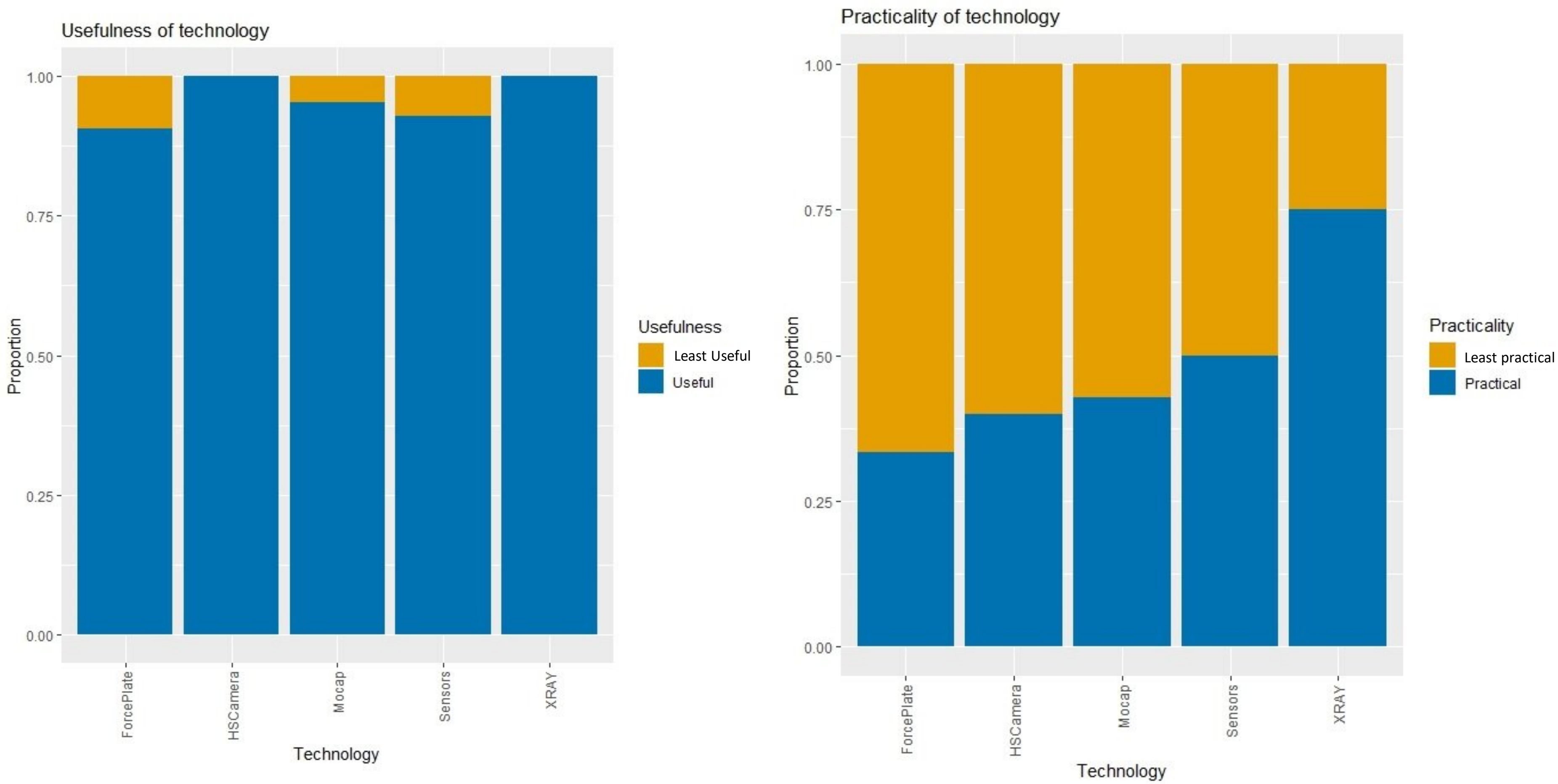


Figure 3.14 Usefulness and practicality of technology for measuring gait parameters, rated by veterinary professionals.

Table 3.9. Summary of agreement between vets, as well as descriptive statistics for round one, theme two questionnaire responses. Consensus was reached if agreement met a pre-defined level of 75%.

Question	Parameter	Consensus Reached	Response	Agreement Between Vets (%)	Number of Participants	Rank Sum	Rank Mean
4	History	✔	Not Useful	7%	28	105	3 .75
			Useful	93%			
	Joint Manipulation	✔	Not Useful	7%	29	115	3.97
			Useful	93%			
	LOAD Questionnaire	✔	Not Useful	10%	10	38	3.80
			Useful	90%			
	Observation of Muscle Wastage	✔	Not Useful	4%	28	110	3.93
			Useful	96%			
	Appreciation of Myofascial Trigger Points	✔	Useful	100%	10	41	4.10
	Owner Description of Symptoms	✔	Not Useful	15%	33	114	3.45
			Useful	85%			
	Palpation	✔	Useful	100%	24	95	3.96

	Probing Questions	✔	Not Useful	12%	25	89	3.56
			Useful	88%			
	Radiography	✔	Not Useful	10%	21	80	3.81
			Useful	90%			
	Response To Treatment	✔	Not Useful	4%	27	111	4.11
			Useful	96%			
	Observation of Stance and Posture	✔	Not Useful	5%	22	83	3.77
			Useful	95%			
	Visually Assess Gait	✔	Not Useful	6%	35	131	3.74
			Useful	94%			
4b	History	✔	Not Practical	7%	28	101	3.61
			Practical	93%			
	Joint Manipulation	✔	Not Practical	10%	29	110	3.79
			Practical	90%			
	LOAD Questionnaire	✔	Practical	100%	10	34	3.40
	Observation of Muscle Wastage	✔	Not Practical	4%	28	111	3.96
			Practical	96%			

	Appreciation of Myofascial Trigger Points	✔	Practical	100%	10	40	4.00
	Owner Description of Symptoms	✔	Not Practical	18%	34	117	3.44
			Practical	82%			
	Palpation	✔	Not Practical	4%	24	93	3.88
			Practical	96%			
	Probing Questions	✔	Not Practical	16%	25	89	3.56
			Practical	84%			
	Radiography	✔	Not Practical	24%	21	69	3.29
			Practical	76%			
	Response to Treatment	✔	Not Practical	7%	27	102	3.78
			Practical	93%			
	Observation of Stance and Posture	✔	Not Practical	10%	22	84	3.82
			Practical	90%			
	Visually Assess Gait	✔	Not Practical	9%	35	137	3.91
			Practical	91%			

7	Cadence	✔	Not Useful	16%	19	65	3.42
			Useful	84%			
	Duty Factor	✔	Not Useful	7%	15	59	3.93
			Useful	93%			
	Footfall Timing	✔	Not Useful	12%	17	63	3.71
			Useful	88%			
	Gait Cycle Duration	✔	Not Useful	6%	16	59	3.69
			Useful	94%			
	Gait Cycle Frequency	✕	Not Useful	29%	14	45	3.21
			Useful	71%			
	Maximum/Minimum Head Difference	✔	Not Useful	13%	23	82	3.57
			Useful	87%			
	Joint Kinematics	✔	Not Useful	7%	14	53	3.79
			Useful	93%			
	Maximum/Minimum Pelvic Difference	✔	Not Useful	9%	22	83	3.77
			Useful	91%			
	Stance Phase	✔	Not Useful	8%	13	49	3.77

			Useful	92%			
	Step Count	✔	Useful	100%	9	35	3.89
	Step Duration	✔	Not Useful	17%	12	41	3.42
			Useful	83%			
	Step Length	✔	Useful	100%	16	58	3.63
	Stride Count	✔	Useful	100%	12	45	3.75
	Stride Duration	✔	Not Useful	11%	18	67	3.72
			Useful	89%			
	Stride Length	✔	Not Useful	9%	22	82	3.73
			Useful	91%			
	Stride Phase	✔	Not Useful	8%	13	50	3.85
			Useful	92%			
	Swing Phase	✔	Not Useful	13%	16	60	3.75
			Useful	87%			
	Vertical Ground Reaction Forces	✔	Not Useful	6%	18	74	4.11
			Useful	94%			
	Walking Speed	✔	Not Useful	6%	17	62	3.65
			Useful	94%			

7b	Cadence	✔	Not Practical	21%	19	64	3.37
			Practical	79%			
	Duty Factor	✕	Not Practical	33%	15	46	3.07
			Practical	67%			
	Footfall Timing	✕	Not Practical	29%	17	52	3.06
			Practical	71%			
	Gait Cycle Duration	✔	Not Practical	19%	16	57	3.56
			Practical	81%			
	Gait Cycle Frequency	✕	Not Practical	36%	14	44	3.14
			Practical	64%			
	Maximum/Minimum Head Difference	✕	Not Practical	26%	23	68	2.96
			Practical	74%			
	Joint Kinematics	✔	Not Practical	21%	14	45	3.21
			Practical	79%			

	Maximum/Minimum Pelvic Difference	✗	Not Practical	27%	22	66	3.00
			Practical	73%			
	Stance Phase	✗	Not Practical	39%	13	38	2.92
			Practical	62%			
	Step Count	✓	Practical	100%	9	34	3.78
	Step Duration	✓	Not Practical	17%	12	40	3.33
			Practical	83%			
	Step Length	✓	Not Practical	19%	16	51	3.19
			Practical	81%			
	Stride Count	✓	Not Practical	8%	12	43	3.58
			Practical	92%			
	Stride Duration	✓	Not Practical	17%	18	62	3.44
			Practical	83%			
	Stride Length	✗	Not Practical	27%	22	70	3.18
			Practical	73%			
	Stride Phase	✗	Not Practical	31%	13	41	3.15

			Practical	69%			
	Swing Phase	✗	Not Practical	31%	16	51	3.19
			Practical	69%			
	Vertical Ground Reaction Forces	✓	Not Practical	22%	18	55	3.06
			Practical	78%			
	Walking Speed	✓	Not Practical	6%	17	65	3.82
			Practical	94%			
10	Force Plates	✓	Not Useful	10%	21	82	3.90
			Useful	90%			
	High Speed Cameras	✓	Useful	100%	10	37	3.7
	Motion Capture	✓	Not Useful	5%	21	76	3.62
			Useful	95%			
	Sensors	✓	Not Useful	7%	14	51	3.64
			Useful	93%			
	XRAY	✓	Useful	100%	16	63	3.94
10b	Force Plates	✗	Not Practical	67%	21	52	2.48
			Practical	33%			

	High Speed Cameras	✕	Not Practical	60%	10	26	2.60
			Practical	40%			
	Motion Capture	✕	Not Practical	57%	21	53	2.52
			Practical	43%			
	Sensors	✕	Not Practical	50%	14	38	2.71
			Practical	50%			
	XRAY	✔	Not Practical	25%	16	53	3.31
			Practical	75%			

Table 3.10 Summary of Kappa values for round one, theme two questionnaire responses, in which vets were asked to indicate the usefulness and practicality of methods, measurements and technology for diagnosing and monitoring canine osteoarthritis. Methods, measurements and technologies were pre-selected by each participant during previous questions.

Question	Response	Subjects	Raters	Kappa	Z value	P value
4 – Usefulness of methods selected for diagnosing osteoarthritis	Useful	12	39	0.113	12	<0.001
4b – Practicality of methods selected for diagnosing osteoarthritis	Practical	12	39	0.106	11.7	<0.001
7 – Usefulness of measurements selected for detecting and monitoring osteoarthritis	Useful	19	35	0.001	1.12	0.265
7b – Practicality of measurements selected for detecting and monitoring osteoarthritis	Practical	19	35	0.006	0.761	0.447
10 – Usefulness of technology selected for detecting and monitoring osteoarthritis	Useful	5	34	0.025	1.41	0.160
10b – Practicality of technology selected for detecting and monitoring osteoarthritis	Practical	5	34	0.026	1.92	0.055

3.3.5 Questionnaire: Round two

The second round of the questionnaire was issued to all veterinary professionals that provided contact details during the first round, of these, 18 participants completed the first question. Despite this, attrition occurred throughout the questionnaire, and only 11 veterinary professionals completed the final question.

When considering the usefulness of parameters which could be measured for the early detection and monitoring of canine osteoarthritis, 10 veterinary professionals agreed that gait cycle frequency would be useful (Table 3.11 & 3.12), achieving consensus for this parameter. Despite this, interrater agreement was slight (Kappa =<0.1). The level of interrater agreement remained slight when rating the practicality associated with measuring the presented gait parameters (Kappa =>0.1), with only one parameter reaching consensus, whereby veterinary professionals agreed that measurement of duty factor was not practical. While consensus was not reached for the remaining parameters, maximum/minimum pelvic difference and stride length were considered most practical, based on level of agreement. The level of interrater agreement increased when considering the practicality of technology which could be used to diagnose and monitor the early stages of canine osteoarthritis, however this remained slight (Kappa=0.1). The practicality of all presented technology achieved the same level of agreement, with no options achieving the pre-defined level of consensus.

When asked to rank diagnostic methods in order of usefulness, whereby the most useful methods for diagnosing and monitoring the early stages of osteoarthritis would be ranked first, palpation was identified as the most useful diagnostic method, followed by the appreciation of myofascial trigger points, and observation of muscle wastage (figure 3.15, Table 3.11 & 3.12).

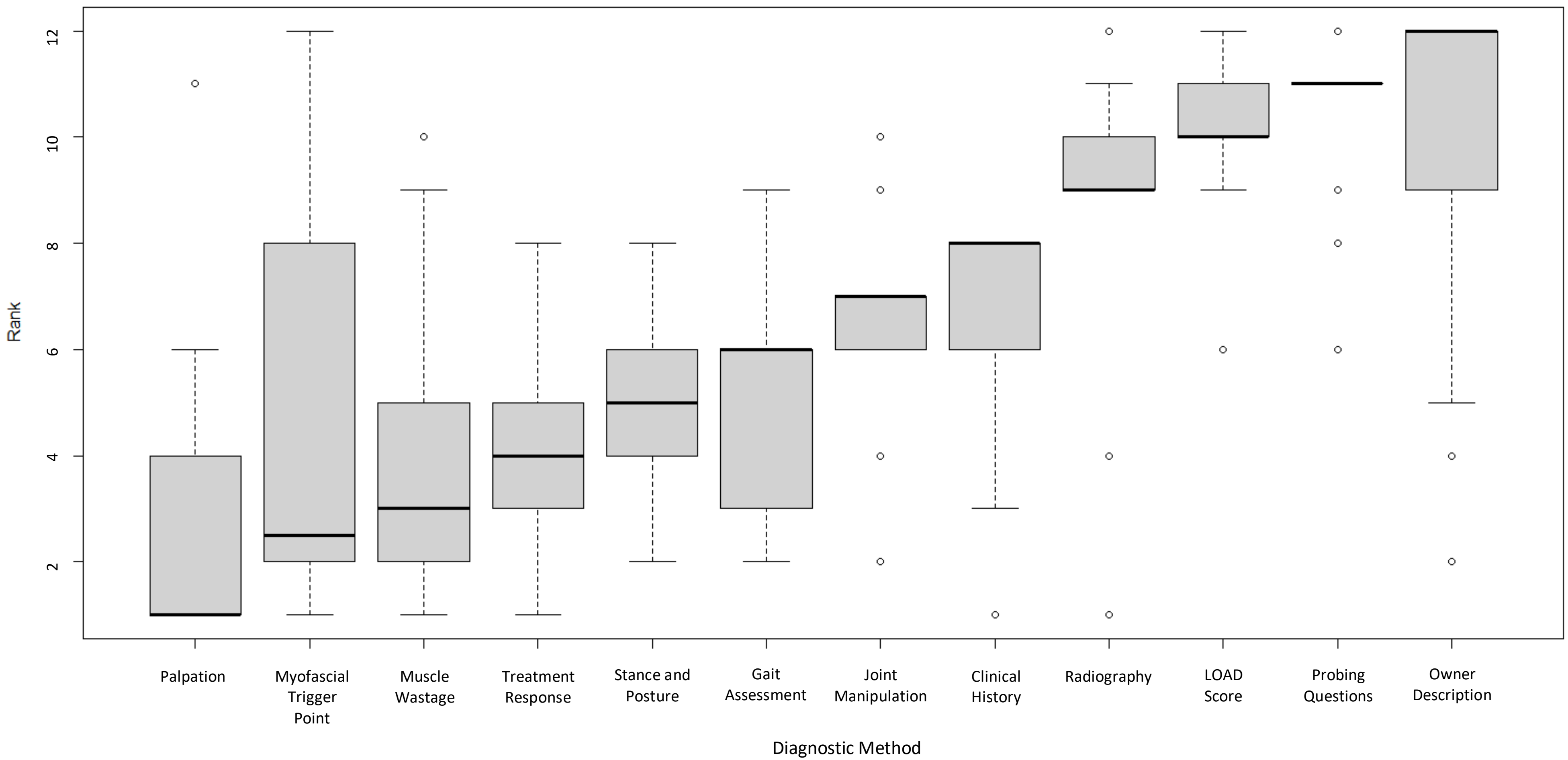


Figure 3.15. Methods for diagnosing and monitoring the early stages of canine osteoarthritis, ranked in order of usefulness.

Conversely, owner description of symptoms was considered the least useful diagnostic method, preceded by the use of probing questions and use of the LOAD questionnaire. When considering the practicality of the presented diagnostic methods, use of the LOAD questionnaire was considered most practical, followed by the appreciation of myofascial trigger points and the observation of muscles wastage (Figure 3.16, Table 3.11 & 3.12). On the other hand, the use of radiography was considered the least practical diagnostic method, preceded by the owner's description of symptoms, and the use of probing questions.

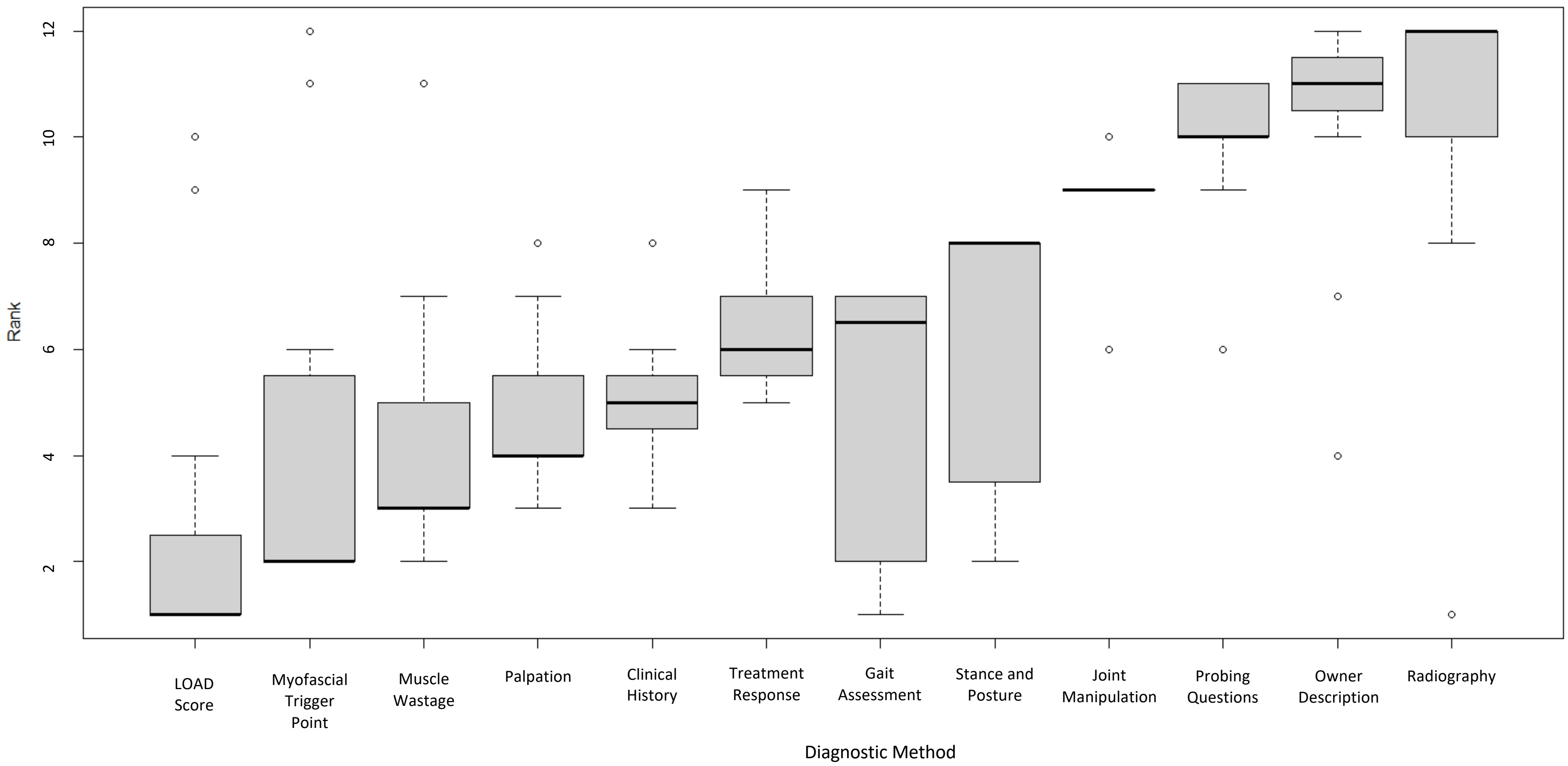


Figure 3.16. Methods for diagnosing and monitoring the early stages of canine osteoarthritis, ranked in order of practicality

When asked to rank the usefulness of measuring specified gait parameters for the early detection and monitoring of canine osteoarthritis, step length was considered the most useful, followed by stride count and step count (Figure 3.17, Table 3.11 & 3.12). Comparatively, gait cycle frequency was ranked as the least useful gait parameter for measurement, preceded by step duration and cadence. When considering the practicality of measuring the presented gait parameters, step count was ranked as the most practical, followed by walking speed and stride count (Figure 3.18, Table 3.11 & 3.12). Conversely, stance phase, gait cycle frequency and duty factor were among the parameters ranked as least practical.

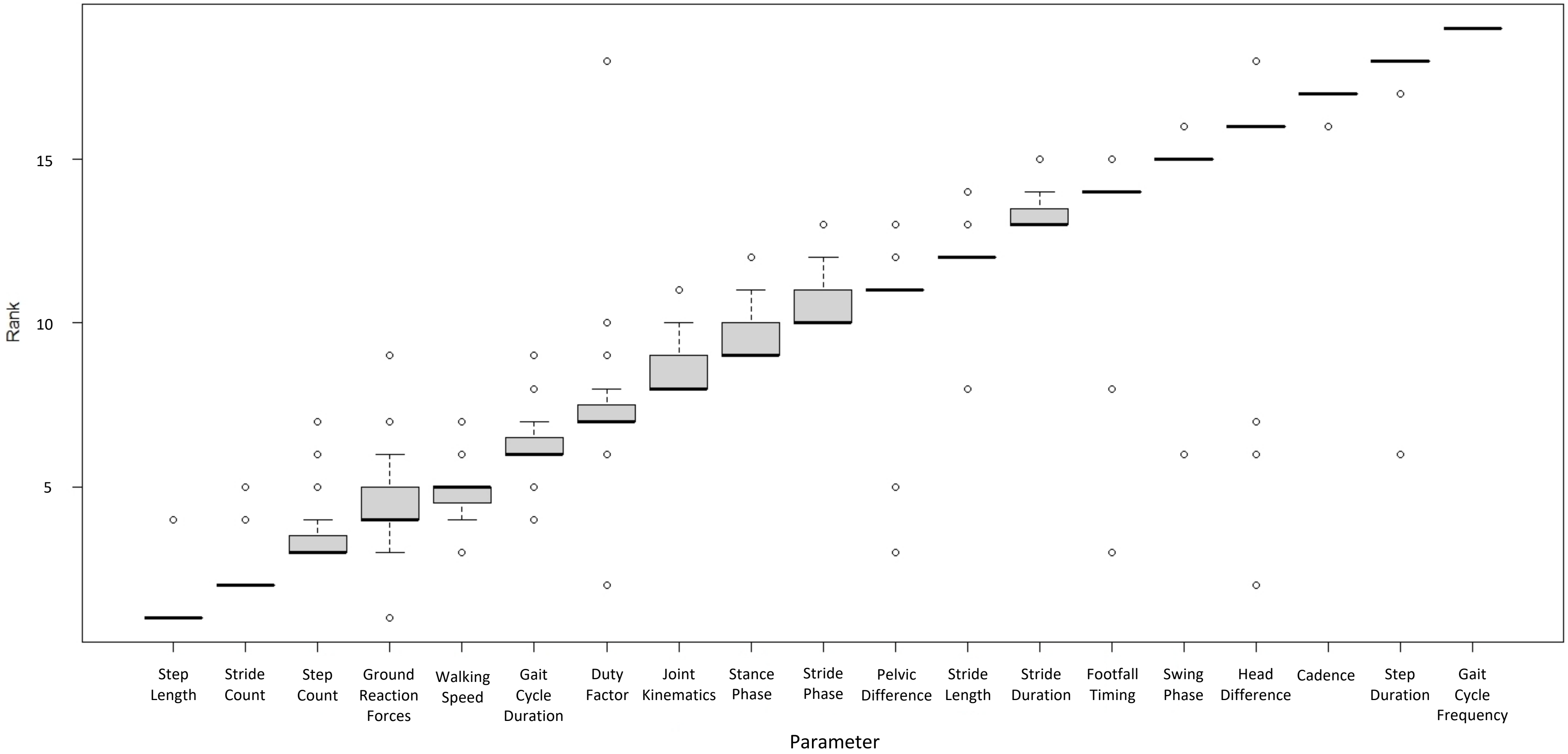


Figure 3.17. Parameters which could be measured in order to detect and monitor the early stages of canine osteoarthritis, ranked in order of usefulness, whereby the first listed parameter is considered the most useful.

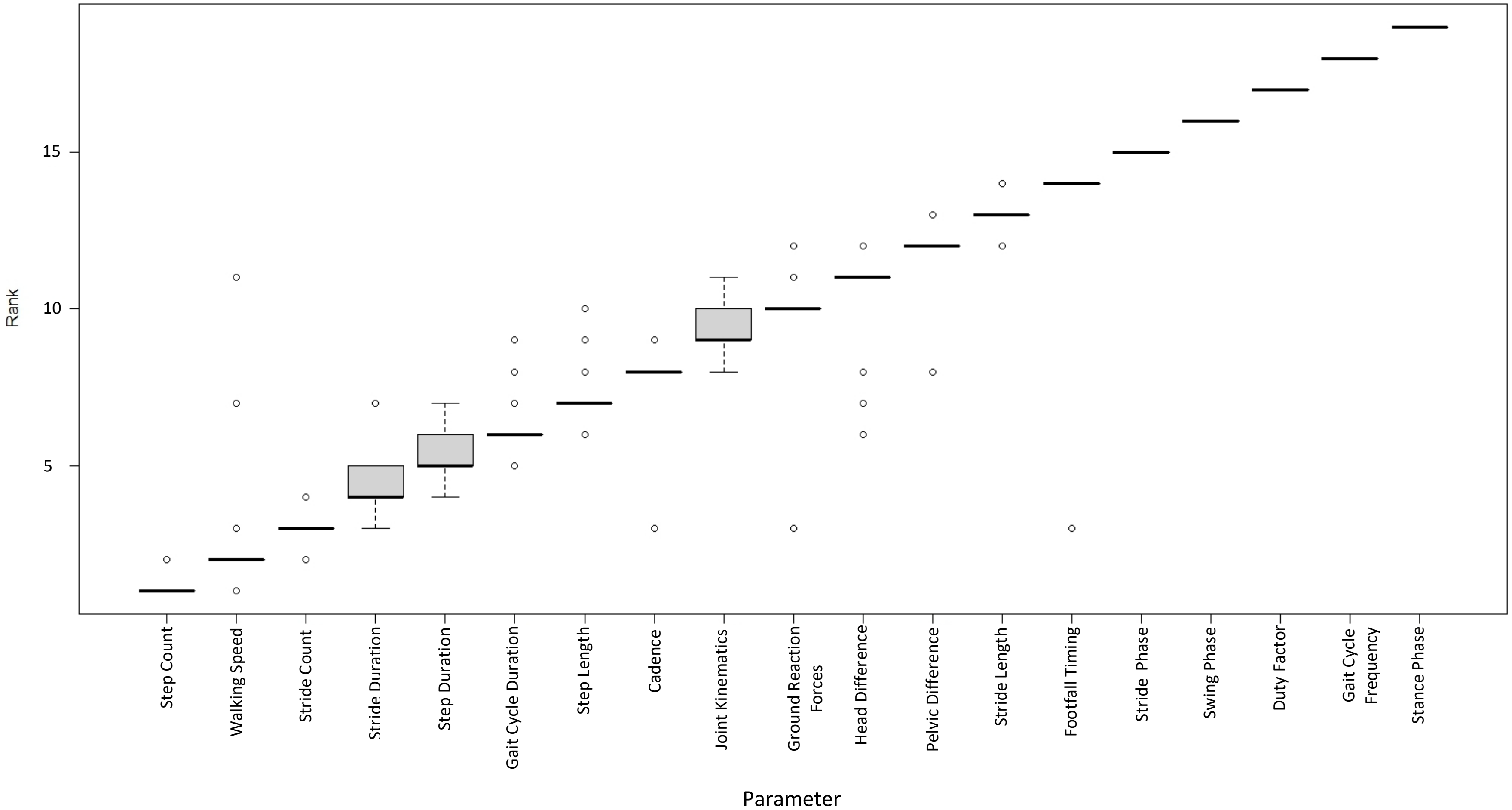


Figure 3.18 parameters which could be measured in order to detect and monitor the early stages of canine osteoarthritis, ranked in order of practicality, whereby the first listed parameter is considered the most practical.

With respect to the technology that could be used to detect and monitor the early stages of canine osteoarthritis, the use of X-Ray was considered the most useful, followed by high-speed cameras (Figure 3.19 & Table 3.11 & 3.12), while force plates were considered the least useful, preceded by the use of sensors. Similarly, the use of X-Ray was considered the most practical diagnostic technology, while force plates were regarded as the least practical (Figure 3.20 & Table 3.11 & 3.12).

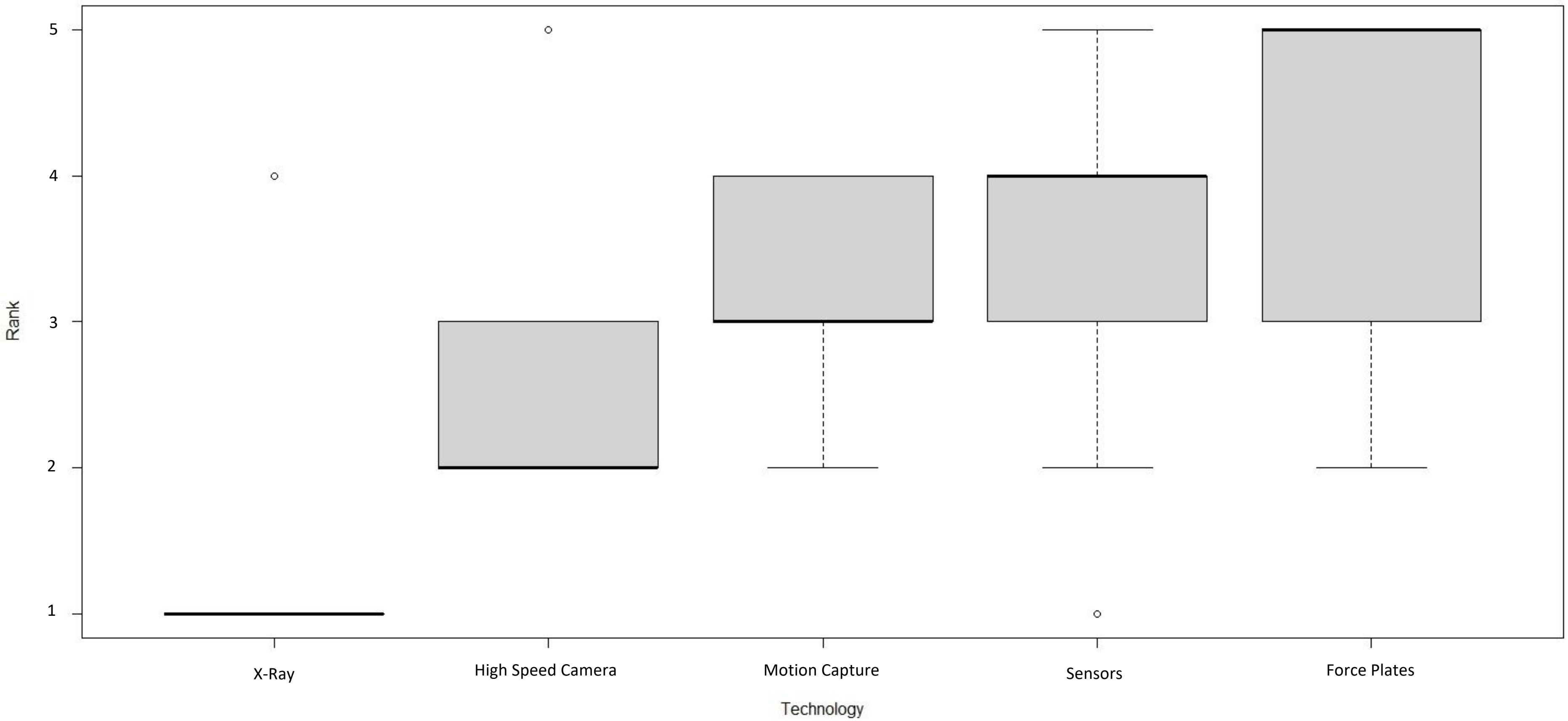


Figure 3.19. Technology which could be used to diagnose and monitor the early stages of osteoarthritis, ranked in order of usefulness, whereby the first technology presented (X-Ray) is the most useful.

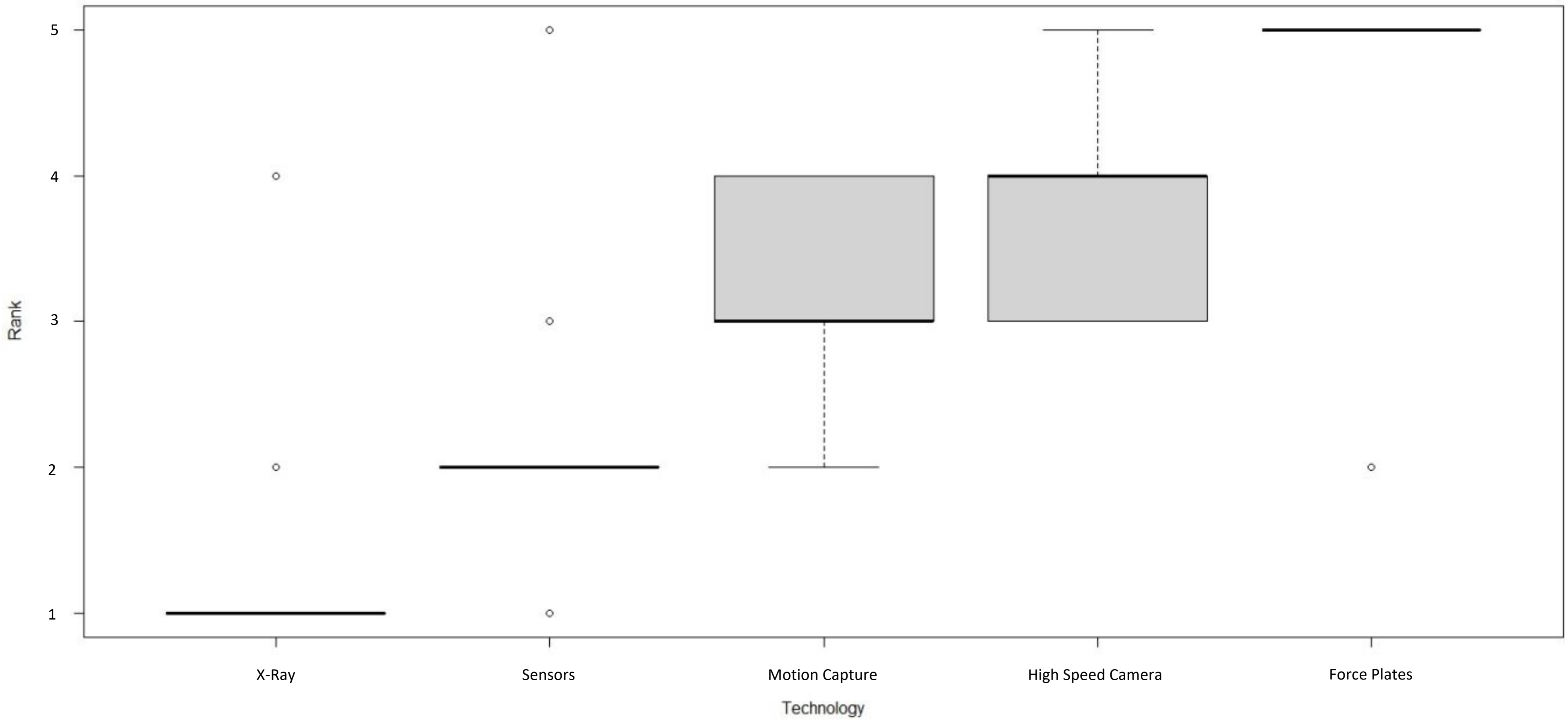


Figure 3.20. Technology which could be used to diagnose and monitor the early stages of osteoarthritis, ranked in order of practicality, whereby the first technology presented (X-Ray) is the most practical.

Table 3.11. Summary of agreement and Fleiss Kappa statistics for round two responses. Parameters which reached consensus at the pre-defined level of 75% are indicated with a tick (✔) in the agreement reached column. Fleiss Kappa was used to explore the level of interrater reliability observed for each question, and this is reported in the Kappa column. The significance of the reported Kappa value is then highlighted in the Significant column, whereby a cross (✗) indicates that a significance level of P <0.05 was not reached.

Question	Parameter	Agreement Reached	Response	Agreement	Number of parameters	Number of participants	Kappa	Z value	P value	Significant
5	Gait Cycle Frequency	✔	Useful	77%	1	13	0.083	0.736	0.462	✕
			Not Useful	23%						
6	Duty Factor	✔	Practical	18%	9	11	0.006	0.142	0.887	✕
			Not Practical	82%						
	Footfall timing	✕	Practical	45.50%						
			Not Practical	54.50%						
	Gait Cycle Frequency	✕	Practical	45.50%						
			Not Practical	54.50%						
	Maximum/Minimum Head Difference	✕	Practical	54.50%						
			Not Practical	45.50%						

	Maximum/Minimum Pelvic Difference	✕	Practical	64%						
			Not Practical	36%						
	Stance Phase	✕	Practical	45.50%						
			Not Practical	54.50%						
	Stride Length	✕	Practical	64%						
			Not Practical	36%						
	Stride Phase	✕	Practical	36%						
			Not Practical	64%						
	Swing Phase	✕	Practical	27%						
			Not Practical	73%						
7	Force Plate	✕	Practical	54.50%	4	11	0.1	1.48	0.138	✕
			Not Practical	45.50%						
	High Speed Camera	✕	Practical	54.50%						
			Not Practical	45.50%						

	Motion Capture	✕	Practical	54.50%						
			Not Practical	45.50%						
	Sensors	✕	Practical	54.50%						
			Not Practical	45.50%						

Table 3.12. Summary of ranked usefulness and practicality of each rated parameter. For each question theme, parameters are ranked from most useful/practical to least useful/practical.

Question Theme	Option, listed in rank order	Median rank	Maximum rank	Minimum rank	Interquartile Range	Number of participants
Usefulness of diagnostic methods	Palpation	1	11	1	3	18
	Myofascial Trigger Point	2.5	12	1	6	
	Muscle Wastage	3	10	1	2.75	
	Treatment Response	4	8	1	1.75	
	Stance and Posture	5	8	2	1.75	
	Gait Assessment	6	9	2	2.5	
	Joint Manipulation	7	10	2	1	
	Clinical History	8	8	1	1.75	
	Radiography	9	12	1	0.75	
	LOAD Questionnaire	10	12	6	0.75	
	Probing Questions	11	12	6	0	
	Owner Description	12	12	2	2.75	
Practicality of diagnostic methods	LOAD Questionnaire	1	10	1	0.75	12
	Myofascial Trigger Point	2	12	2	3.25	
	Muscle Wastage	3	11	2	1.5	
	Palpation	4	8	3	1.25	
	Clinical History	5	8	3	0.5	
	Treatment Response	6	9	5	1.25	
	Gait Assessment	6.5	7	1	5	
	Stance and Posture	8	8	2	4.25	
	Joint Manipulation	9	10	6	0	
	Probing Questions	10	11	6	1	

	Owner Description	11	12	4	0.5	
	Radiography	12	12	1	2	
Usefulness of gait parameters	Step Length	1	4	1	0	16
	Stride count	2	5	2	0	
	Step count	3	7	3	0.25	
	Vertical Ground Reaction Forces	4	9	1	1	
	Walking Speed	5	7	3	0.25	
	Gait Cycle Duration	6	9	4	0.25	
	Duty Factor	7	18	2	0.25	
	Joint Kinematics	8	11	8	1	
	Stance Phase	9	12	9	1	
	Stride Phase	10	13	10	1	
	Maximum/Minimum Pelvic Difference	11	13	3	0	
	Stride Length	12	14	8	0	
	Stride Duration	13	15	13	0.25	
	Footfall Timing	14	15	3	0	
	Swing Phase	15	16	6	0	
	Maximum/Minimum Head Difference	16	18	2	0	
	Cadence	17	17	16	0	
	Step Duration	18	18	6	0	
	Gait Cycle Frequency	19	19	19	0	
	Step count	1	2	1	0	13
	Walking Speed	2	11	1	0	

Practicality of gait parameters	Stride Count	3	4	2	0	
	Stride Duration	4	7	3	1	
	Step Duration	5	7	4	0	
	Gait Cycle Duration	6	9	5	0	
	Step Length	7	10	6	0	
	Cadence	8	9	3	0	
	Joint Kinematics	9	11	8	1	
	Vertical Ground Reaction Forces	10	12	3	0	
	Maximum/Minimum Head Difference	11	12	6	0	
	Maximum/Minimum Pelvic Difference	12	13	8	0	
	Stride Length	13	14	12	0	
	Footfall Timing	14	14	3	0	
	Stride Phase	15	15	15	0	
	Swing Phase	16	16	16	0	
	Duty Factor	17	17	17	0	
	Gait Cycle Frequency	18	18	18	0	
	Stance Phase	19	19	19	0	
Usefulness of diagnostic technology	X-Ray	1	4	1	0	14
	High Speed Camera	2	5	2	1	
	Motion Capture	3	4	2	0.75	
	Sensors	4	5	1	0.75	
	Force Plates	5	5	2	1.75	
	X-Ray	1	4	1	0	13

Practicality of diagnostic technology	Sensors	2	5	1	0	
	Motion Capture	3	4	2	1	
	High Speed Camera	4	5	3	1	
	Force Plates	5	5	2	0	

3.4 Discussion

We implemented the Delphi consultation framework to seek expert opinion regarding the use of sensor technology in veterinary therapeutics, and for the diagnosis and long-term monitoring of canine osteoarthritis. The study took place in three stages, beginning with a discussion board, before completing two questionnaire rounds. Throughout each stage of the study, the topic was divided into two themes, whereby the first focussed on the use of sensors in veterinary therapeutics, with emphasis on the use of a proposed novel device, while the second focussed on the use of such technology for the early detection and long-term monitoring of canine osteoarthritis. Although veterinary professionals were invited to participate in both themes, pet owners were invited to contribute to theme one only.

3.4.1 Discussion board

The discussion board consolidated knowledge obtained throughout the literature search, highlighting no withstanding gaps associated with theme one, while identifying potential methods for diagnosing canine osteoarthritis, which had not been extracted from the literature. Responses indicated an interest in the use of sensor technology in veterinary therapeutics, whereby measurement of glucose and temperature were identified as having the most potential to benefit the management of conditions such as feline diabetes, as well as the identification of hypothermia. Similarly, while there was variation in the common methods used for detecting and monitoring canine osteoarthritis, additional parameters which could be incorporated into this process, measurable by the proposed device, were identified. While it was suggested that the device would be of most interest to vets and veterinary physiotherapists, integration of the device into veterinary practice and healthcare highlighted a range of barriers, including durability, cost, and complexity. Although the discussion board consolidated knowledge surrounding the use of sensor technology in veterinary therapeutics, and for the diagnosis and long-term monitoring of canine osteoarthritis, the variation in responses confirmed the need for further clarification surrounding the issue, using a series of questionnaires.

3.4.2 Questionnaire: round one, section one

The first section of the questionnaire aimed to address the use of sensor technology in veterinary therapeutics, including how such technology could be used to benefit the pathway to effective diagnosis and treatment.

3.4.3 Round one, section one: parameters of importance

Most owners and veterinary professionals considered that the proposed device could support the early detection, diagnosis, and management of health conditions in dogs and cats, with emphasis placed upon the identification and monitoring of osteoarthritis, and feline diabetes, by measuring parameters including glucose, temperature, and activity count. Although activity count was regarded by each stakeholder to be beneficial when specifically considering osteoarthritis, consensus was not reached when considering the benefit of measuring this parameter in general. Despite the lack of consensus for this parameter, no further questionnaire rounds were completed for theme one due to the mean agreement, calculated for the entire questionnaire, reaching consensus at the pre-defined level of 75%.

Conversely each stakeholder regarded the general measurement of parameters such as glucose and body temperature to be useful, without the need for additional context. The usefulness associated with the measurement of glucose and body temperature may be due to the level of information such parameters can infer regarding the overall health status of the animal from which they are measured, whereby parameters such as activity counts may offer little benefit when measured beyond the scope of specific conditions. As such, the expected usefulness of some parameters may depend on the prevalence and perceived severity of the condition with which they are associated, whereby osteoarthritis is often underdiagnosed and misunderstood (Belshaw et al 2020a), perhaps accounting for the lack of consensus regarding the usefulness of activity-based parameters when measured in general. Variation was also observed in the usefulness associated with measuring cortisol, whereby pet owners considered this to be the most useful parameter measurable using the proposed device, while veterinary professionals failed to reach consensus. The dissimilarity in responses between the two groups could be due to a lack of clarity regarding the nature of cortisol, and the inferences that could be made by measuring this parameter, whereby participants with less understanding or experience of this parameter may misinterpret its usefulness (Chmelíková et al 2020). Alternatively, contrasting responses may reflect differing priorities, whereby owners are not experts (except of their own dog/cat perhaps) and therefore may be most interested in indicators of their pet's overall welfare, as this is something they can manage independently. Conversely, vets are experts and may prioritise clinical measures with diagnostic potential. Due to the variation in expertise, disagreement between the two demographic groups should not be used to undermine the knowledge of the veterinary professionals. Instead, the knowledge of vets should be considered the gold standard, with differences in opinion highlighting a gap in owner expertise. Despite this, it is useful to understand what is valued by the owner as these will be a key user of the proposed technology.

3.4.4 Round one, section one: Deployment of the proposed device

When considering the deployment of the proposed device within veterinary therapeutics, veterinary professionals and pet owners shared similar views regarding potential users, and their locations. It was expected that the novel device would be best placed within specialist referral practices and paraveterinary settings, such as physiotherapist clinics, in which veterinary nurses and physiotherapists were predicted to be among the most interested users. Similarity in responses between the stakeholders may indicate a shared understanding of the role each professional plays within the veterinary healthcare setting, whereby owner understanding may be derived from experiences of veterinary healthcare with their dog and/or cat. Despite this, veterinary professionals and animal owners disagreed on the predicted benefit of the device when used within non-clinical settings, such as the owners' home, whereby veterinary professionals believed use of the device in such locations would not be beneficial. The view that such a device would not be beneficial when used in a non-clinical setting may be due to question phrasing, in which the device's use was not defined. As such, the lack of agreement among veterinary professionals may be due to misconceptions surrounding what the use of the device entails, whereby use in a diagnostic capacity would understandably require the input of veterinary professionals, while use for the ongoing collection of health data would not. The limited benefit associated with the use of the device in non-clinical settings may also reflect the perceived ability of owners to incorrectly implement technology and use subsequent data to misinform decisions when seeking veterinary attention (Springer et al 2024). Despite this, human and pet activity monitors are becoming ubiquitous (Harper et al 2023), meaning that owners are likely to have transferrable understanding and experience, which could support their use of the device. Moreover, the increasing availability of medical information across a multitude of platforms (Kogan et al 2018) may improve understanding and awareness of their pet's health, perhaps instilling confidence that well informed decisions could be made in response to potential health alerts, should such a device be used in non-clinical settings.

3.4.5 Round one, section one: supporting the relationship between vets and owners

Upon establishing the potential users of the proposed device, it was important to consider the extent to which the novel technologies could support the relationship between vets and owners. While communication is often viewed as a pitfall when considering the pathway to diagnosis and effective treatment (Hughes et al 2018), whereby health literacy and appointment times may serve as factors which limit information exchange between vets and owners (Belshaw et al 2016; Sørensen et al 2012), both stakeholders suggested this could improve with the use of novel technologies. Further elaboration indicated that the use of data would be a key factor in the improvement of communication, suggesting that the introduction of quantitative measures could remove subjectivity and improve clarity when describing problems, and monitoring the effectiveness of treatment. Despite this, the accessibility of data collected by the device may depend upon the format in which it is presented, whereby each group considered the use of graphs to be the most convenient, while raw data was considered least convenient. It is likely that graphs were preferred by both stakeholders, as such a format can be used to visually highlight trends in data, perhaps leading to better understanding of the data, while facilitating the decision-making process (Tait et al 2010). Raw data was understandably ranked as the least useful by both stakeholder groups. This is likely due to the skill and time required to read, interpret, and identify trends in the data before processing has taken place. Although veterinary professionals did not consider the use of text to be a convenient format for the presentation of data, pet owners considered this format to be as convenient as the use of tables, a factor which may be due to the expectation that the use of text would contextualise the data, perhaps making this more accessible to pet owners.

3.4.6 Round one, section one: benefits of using the proposed device

The benefits associated with the use of novel technologies within veterinary healthcare support the indication that most participating pet owners and veterinary professionals would be willing to use the proposed device, with small proportions of each stakeholder group remaining unsure. The lack of certainty regarding potential use centred largely around practicality as well as trust in the device's ability to work as expected, whereby vets and owners stated that their use of the device would depend on this first being trialled by others. While pet owners and veterinary professionals highlighted practicality concerns for animals who do not typically wear collars, it was suggested that these could be overlooked if the animal had a medical condition which would benefit from the continuous monitoring offered by the device. More robust barriers to the use of the proposed device highlighted by veterinary professionals included the time taken to use the device, its availability, and its ability to integrate with current practice systems. While the identification of such barriers conflict with the perception that use of the proposed device could assist in the delivery of effective practice, it is possible that the described concerns are influenced by the mounting pressures faced by vets following increased pet ownership (McMillan et al 2024). As concerns regarding the time taken to use the device, as well as its potential integration with current practice systems would have a disproportionate impact on veterinary professionals, the suggested inclusion of veterinary surgeons in the development of the device may be a key method for overcoming potential barriers to its use. Pet owners also raised concerns regarding the availability of the device, with additional barriers including uncertainty surrounding the usefulness and complexity of the proposed technology. The identification of such barriers may indicate a lack of experience with sensor-based devices, whereby most participating pet owners had not previously used pet activity monitors, perhaps leading to a lack of confidence in personal ability to use the device and interpret subsequent data. When considering methods for overcoming potential barriers, it is logical the self-specified option of the assurance of health benefits would be rated as most important based on level of consensus, addressing the concern regarding the usefulness of the device. Despite this, the low importance assigned to the simplicity of the user interface suggests that apprehensions regarding complexity may involve the interpretation of data collected by the sensor, as opposed to the initial device set-up.

3.4.7 Questionnaire: round one, theme two

Before investigating the potential use of sensor technology to support the diagnosis and management of canine osteoarthritis, it was to necessary gauge owner understanding of the condition, as well as their ability to recognise associated symptoms. This was achieved by seeking the opinion of veterinary professionals during the second theme addressed by the series of questionnaires. While veterinary professionals agreed that owner ability to recognise the symptoms of canine osteoarthritis was poor (as previously suggested by Belshaw et al (2020a)), no consensus could be reached regarding their overall understanding of the condition, despite a majority of participants rating this as poor. It is likely the limited aptitude of owners for recognising the symptoms of osteoarthritis is due to the subtle and often intermittent nature of indicators associated with the condition, particularly during the early stages (Belshaw 2017). Additionally, the overall understanding of osteoarthritis is likely to be skewed by misconceptions surrounding the condition, whereby many owners regard this as an inevitable by-product of ageing (Belshaw et al 2020a). Despite this, the lack of consensus among veterinary professionals may be due to the consideration of owners with experience of effectively managing the condition following their dog's diagnosis.

3.4.8 Questionnaire: Round two

Throughout the first questionnaire round, veterinary professionals agreed that all selected methods for diagnosing and monitoring canine osteoarthritis were both useful and practical, reaching a pre-defined level of consensus for each method. A subsequent questionnaire then sought to confirm the rank order of the practicality and usefulness of each method, based on the previous level of consensus. While palpation was regarded as the most useful method for diagnosing canine osteoarthritis, this technique was regarded as the fourth most practical option. As palpation would involve physically touching and manipulating the affected area (Formenton et al 2025), it is possible that the limited practicality of this method is due to the perhaps unpredictable response of the affected individual. While use of the LOAD questionnaire was ranked as the 10^{th} most useful diagnostic method from a total of 12 options, this method of diagnosing and monitoring osteoarthritis was ranked first in terms of practicality. The low ranking assigned to the usefulness of the LOAD questionnaire was particularly interesting when considering how well validated this staging tool is (Walton et al 2013), particularly when compared to the lesser validated methods which have been assigned a higher rank.

The low ranking assigned to the usefulness of the LOAD questionnaire may be due to the lack of a physical component associated with this diagnostic method, as well as a reliance on the owner's ability to properly interpret and respond to the prescribed questions. Conversely, the method's high ranking in terms of practicality may reflect the fact that the questionnaire could be completed prior to a consultation, during which results could be used to advise subsequent diagnostics and treatment, perhaps limiting the extent to which an owner would be required to detail their dog's symptoms. Although the perceived practicality of the LOAD questionnaire may appear to conflict with the low ranking assigned to the owner's description of symptoms, and responses to probing questions, data collected by the survey is numeric, limiting the extent to which responses can be miscommunicated by owners, or misinterpreted by vets.

3.4.9 Round two: use of the proposed device to support the diagnosis of canine osteoarthritis.

To establish how the proposed device could assist in the diagnosis and management of canine osteoarthritis, consideration of the usefulness and practicality of measurable gait parameters was required. While participating vets agreed that the measurement of all selected gait parameters would be useful, consensus regarding the practicality of nine parameters could not be reached. Although the use of a subsequent questionnaire highlighted agreement regarding the impracticality of measuring duty factor, consensus could not be reached for the eight remaining parameters, despite the use of a binary rating system. As consensus could not be achieved for the remaining parameters, while each of these were ranked among the least practical for measurement, it was predicted that agreement would not improve with subsequent surveys, and therefore the rank order of practicality obtained during the second questionnaire round was accepted. When considering the ranked order of gait parameters, step length, stride count, and step count were regarded as the most useful. While this ranking may be based on the perception that arthritic individuals may take fewer and shorter steps than their sound counterparts, this is not supported by Chapter 1. While step count and stride count also featured among the three parameters for which measurement was considered to be most practical, step count was replaced with walking speed. It is likely the specified parameters were regarded among the three most practical due to the ease in which these could be calculated while simply observing the dog's gait, whereby parameters such as step length would require more granular measurement and an increased time commitment.

3.4.10 Round two: Measurement of selected gait parameters

To ascertain how best to measure the selected gait parameters, it was important to understand which technology would be both useful and practical when deployed within the veterinary healthcare sector. While veterinary professionals reached consensus regarding the usefulness of each presented technology during the first round of the questionnaire, agreement regarding the practicality of these reached consensus for only one option, the use of radiography. As such, a second survey was required, during which the practicality of remaining diagnostic technology was considered using a binary rating scale. Although a majority of veterinary professionals considered each option to be practical, agreement did not reach consensus at the pre-defined level of 75%. Although each option was considered to be more practical when compared to responses collected in the previous round, this may be due to a reduction in participants as a result of attrition. As consensus could not be reached despite a binary rating scale, it was considered that an improved level of agreement was unlikely to result from the use of additional questionnaire rounds, leading to the acceptance of the obtained rank order. When considering the ranked order of diagnostic technologies, radiography was regarded as the most useful and practical option. Conversely, the use of force plates was the lowest ranked option in terms of both practicality and usefulness. Although the low rank assigned to the usefulness of force plate technology conflicts with high rank attained by the measurement of vertical ground reaction forces, such inconsistencies may reflect inexperience with the specified technology, and an unfamiliarity with the parameters they measure. While the use of sensors for the measurement of specified gait parameters was ranked fourth in terms of usefulness, this placement may be due to the novel nature of the proposed device, whereby the perceived utility may be subject to change with experience. Conversely, the same technology was ranked second in terms of practicality, perhaps highlighting the potential for sensor devices to be integrated into veterinary healthcare for the diagnosis and management of conditions such as canine osteoarthritis.

3.4.11 Limitations

Although the implementation of the Delphi consultation process facilitated the collection of expert opinion regarding the use of sensor technology in veterinary therapeutics, and for the diagnosis and long-term monitoring of canine osteoarthritis, the study was not without limitations, several of which involved the discussion board. While the discussion board process captured the opinion of five vets, additional stakeholders of interest included paraveterinary professionals, such as physiotherapists, veterinary nurses, and hydrotherapists, as well as cat and dog owners. As the specified stakeholders were not recruited for participation in the discussion board, it was not possible to capture the opinion of all target demographics, meaning that some knowledge gaps may have gone unidentified, and unaddressed, prior to designing the survey. Furthermore, it was not possible to trial the phrasing of questions and definitions for all target audiences as per the Delphi Consultation framework presented by Leach et al (2008). While it is possible that one style of question phrasing and structuring would not be appropriate for each of the identified stakeholders when considering varying knowledge and experience, the lack of representation from these groups within the discussion board meant that no adjustments could be recommended. As the structure and phrasing of questions and definitions received no negative feedback from participating vets, similar structure and phrasing was implemented during the survey design, perhaps impacting the quality of responses received from additional stakeholder groups at later stages of the study.

Failure to recruit representatives from all stakeholders likely involved the fact that the initial registration process was lengthy and complex. After completing the registration form, participants were required to log in to the WordPress website, using anonymous credentials provided via email, before navigating to the discussion board page, accessible using a shared password. Although it is possible that some prospective users were unable to participate due to the delivery of login credentials to their junk email folder, the time required to register for participation and subsequently log into the discussion board was likely to be a key factor dissuading participation from some target stakeholder groups.

Once users had successfully accessed the discussion board, subsequent participation required interaction with the forum at least once per day, for a minimum of two consecutive days, whereby repeated engagement was encouraged to increase the likelihood of potential discussion between participants. Despite this, repeated interaction could not be guaranteed, and while users were able to access the discussion board at any time, the likelihood of multiple users being active at any one time was low, restricting the level of engagement between participants. While efforts to encourage simultaneous participation could have involved publishing new questions at specified times across several days, doing so would have necessitated a larger time commitment from participants, with the potential for attrition throughout the process. Instead, all questions were published on the day of activation, giving all participants equal opportunity to respond, regardless of their level of engagement.

Implementation of the discussion board facilitated the collection of opinions from target stakeholders regarding the proposed issue, while abiding by social distancing and lockdown measures enforced in response to the Coronavirus pandemic. This alternative approach to an in-person scoping meeting was demonstrated by Rioja-Lang et al (2020a) and consolidated understanding of the proposed issue, while addressing withstanding knowledge gaps following the initial literature search. Although the discussion board was impacted largely by the failure to recruit representatives from each target stakeholder, the identification of this problem at a relatively early stage in the study highlighted the need for more targeted recruitment throughout the questionnaire stages.

The recruitment of participants belonging to the pet owner demographic improved during the questionnaire stages, largely due to the advertisement of the study using social media platforms such as Facebook and Twitter. Despite this, the recruitment of veterinary professionals was poor, with a reduced number of participants when compared to dog and cat owners. Although a range of recruitment strategies were implemented, including emails to known contacts and identified practices, as well as advertisement on social media and in veterinary journals, it is possible that the reduced uptake was due to the rising pressures faced by veterinary professionals following the coronavirus pandemic recent rise in pet ownership (McMillan et al 2024).

Once veterinary professionals were recruited, a high rate of attrition was observed within and between questionnaire rounds. While 59% of participating vets completed the first questionnaire in its entirety, only 40% then proceeded to the second questionnaire, whereby a total of 61% of participants completed the entire survey. While attrition rates vary between studies, a minimum rate of 20-30% can be anticipated between rounds (Bardecki 1984). Although the level of attrition observed throughout this study exceeds the minimum expected rate, this was perhaps influenced by an array of factors, the first of which involved the use of lengthy and repetitive questions, for which definitions were required. While the creation of a pilot survey, in collaboration with all stakeholder groups, may have ensured that appropriate question phrasing and structures were implemented, the lack of participant interaction with the discussion board meant this was not a viable option.

Additional limitations include the lack of demographic information recorded from participants, reducing the extent to which responses could be analysed. While there were no inclusion criteria surrounding the number of years of post-qualification experience held by each participant, the availability of such information would have allowed for a generational comparison on the views of sensor technology, while perhaps providing additional context when interpreting responses.

Although most questionnaire responses were collected using a five-point Likert scale, the first question, regarding the usefulness of measurable parameters, mistakenly included a four-point scale. As the use of a four-point Likert scale may have increased the likelihood of achieving consensus, due to the removal of a scale point, scales should have been consistent across all questions. When considering the remaining questions, for which five-point scales were implemented, it became apparent that no 'neutral' options were made available, whereby an example scale included the following points: not at all practical, somewhat practical, practical, very practical, and extremely practical. As no neutral option such as 'neither practical nor impractical' was included, responses were more likely to be positive, for instance 'practical' or 'useful', when implementing binary scales (Figure 2). While it was hoped that the lack of neutral options would limit the extent to which participants could remain impartial, it is possible that such an approach may have unfairly weighted responses (Guy and Norvell 1977). Such weighting may also be a result of questionnaire structure, in which multiple-choice questions identified the parameters to be rated in subsequent Likert scale responses, whereby participants were unlikely to negatively rate the parameters they had selected during previous questions. To avoid inadvertently influencing responses, the structure of the questionnaire could have been reversed, instructing participants to rate all presented parameters, before using multiple choice questions to highlight the parameters regarded as most useful/practical for example.

While further limitations to the study could include the failure to seek consensus for theme one responses, it was considered that sufficient information had been gathered to treat the initial round as a scoping exercise, highlighting an interest in the use of sensor technology for veterinary therapeutics, without the need for subsequent surveys. Despite this, the lack of follow-up surveys meant that veterinary professionals and pet owners were not given the opportunity to establish a rank order of parameters relevant to each question, as described by Rioja-Lang et al (2020b). This meant that although it was possible to identify the parameters for which participants had reached consensus, the relative importance of the parameters to each demographic group could not be established, perhaps limiting the context that could be drawn from responses.

A final limitation perhaps involves the use of incentivised participation. While it was considered that the use of incentives would reduce attrition and increase the rate of participation, this approach potentially biased the collected responses in support of the proposed device, instead of reflecting the genuine opinion of the participant, this problem was previously highlighted by James and Bolstein (1990).

3.5 Conclusion

The Delphi consultation framework was implemented to seek expert opinion regarding the use of novel sensor technologies in veterinary therapeutics, as well as for the detection and long-term monitoring of canine osteoarthritis. Throughout the process, most participating pet owners and veterinary professionals agreed that they would be willing to use the proposed device, with the indication that this could assist in the identification and management of conditions including osteoarthritis and feline diabetes, with the measurement of parameters including activity counts and glucose. Despite the benefits associated with the use of novel technologies, each demographic highlighted potential barriers to its implementation, suggesting that while the proposed device could improve the pathway to diagnosis and effective treatment, careful management would be required to ensure this did not cause an additional strain to the vet/owner relationship.

When considering the use of the proposed device specifically for the detection and monitoring of canine osteoarthritis, veterinary professionals suggested that the ability of owners to recognise the symptoms of osteoarthritis was poor, indicating an unmet need for assistance at the initial stage in the pathway to diagnosis and effective treatment. While the use of sensor technologies could support the detection of disease, the parameters measured by such devices should be practical, with validated diagnostic potential. Veterinary professionals considered step count to be the most practical parameter for measurement using the proposed device, as well as the third most useful parameter, behind step length and stride count. As step count can be measured using the sensor device, while step length and stride count could be derived from the same parameter, the diagnostic potential of step count should be investigated further.

Subsequent studies will explore the diagnostic potential of the gait parameter step count, by validating a step detection algorithm for use with arthritic dogs, before comparing the step counts of sound and arthritic dogs, using accelerometer data, and supporting video footage. As the use of sensor technology was also perceived to be useful for the healthcare of cats, while osteoarthritis affects approximately 90% of cats exceeding the age of 12 (Bonecka et al 2023), an additional study will explore the generalisability of the pedometer algorithm for the detection of feline steps.

Chapter 4. Cataloguing the gait of sound and arthritic dogs.

4.1 Introduction

Canine osteoarthritis (OA) is a chronic progressive disease that affects up to 80% of dogs over the age of eight (Anderson et al 2018), and up to 20% of dogs exceeding the age of one (Fritsch et al 2010). Recognised as the most common joint disease diagnosed in both human and veterinary medicine (Anderson et al 2018), OA causes the loss and dysfunction of cartilage in synovial joints, ultimately leading to impaired function within the affected joint, as well as chronic pain (Alam et al 2011; Anderson et al 2020). While OA can occur both idiopathically, as well as secondary to injury, it is associated with a host of contributing factors, including exercise type and intensity, as well as body weight, breed, and age (Anderson et al 2020; Mele 2007). Despite the prevalence of OA, the condition often remains undiagnosed until progressing to later stages, often at routine and unrelated veterinary appointments such as vaccinations or health checks (Cachon et al 2018). The problem of delayed diagnosis is associated with a range of factors including short appointment times and imperfect diagnostic methods, as well as the nature of associated symptoms.

The physical and behavioural indicators of OA are often subtle and intermittent, particularly during the early stages of the disease (Belshaw 2017), with such symptoms including inactivity stiffness, lameness, and a reluctance to exercise or play (Belshaw et al 2020a; Pettitt and German 2015). As the presentation of the described indicators can fluctuate based on factors such as temperature, and the intensity of activities undertaken in previous days (Belshaw 2017), it rational to believe that such symptoms could be overlooked or misinterpreted, and that some indicators of OA are normal by-products of aging (Belshaw et al 2020a; Lascelles et al 2002).

Once OA indicators are identified, the diagnostic process typically includes a visual assessment of the dog's gait and ability to rise, as well as a physical examination of the affected joint, supported by the owner's description of observed symptoms (Belshaw et al 2020a). Despite the multifaceted approach, there are many flaws associated with the diagnostic process, beginning with the short duration of veterinary appointments. As an appointment in a general practice veterinary surgery is typically restricted to just 10 minutes (Robinson et al 2016), while OA symptoms are often sporadic in nature, it becomes reasonable to consider that indicators of concern to the owner may not be demonstrated during the consultation, thus avoiding veterinary evaluation. A further flaw associated with the diagnostic process is the need for owner insight, which must be both reliable and effectively communicated, whereby such prerequisites may be impacted by short or rushed appointments (Belshaw et al 2018) and subjectivity. Although this issue is addressed, in part, by the use of clinical metrology instruments, such as the Liverpool Osteoarthritis in Dogs (LOAD) score, the success of such tools relies on the ability of owners to correctly interpret and respond to questions.

Once diagnosed, a multimodal approach to managing the condition is often implemented. First, non-steroidal anti-inflammatory (NSAID) and analgesic medications are used to control chronic pain (Bound et al 2011; Fritsch et al 2010), while measures such as adjustments to the length, duration, and intensity of exercise can be enforced to delay the progression of the disease (Bound et al 2010), preserving the affected dog's quality of life (Cachon et al 2018). As the treatment and management of OA first requires the identification and subsequent diagnosis of symptoms, solutions to the problem of delayed diagnosis must be identified, in order to reduce the impact of the condition on the individual's health and welfare.

When considering potential solutions to the problem of delayed diagnosis, inspiration can be found from human medicine, in which the diagnostic potential of sensor technologies is demonstrated. Although some technologies applied to human medicine are not widely available in veterinary healthcare, such as those required for gait analysis and weight bearing evaluation (Alves and Innes 2023), affordable alternatives include accelerometers, which, having been applied to the study of human joint kinematics for over 30 years (Fong and Chan 2010), have validated diagnostic potential for identifying gait abnormalities, such as those associated with Parkinson's disease (Shalachetzki et al 2017).

Use of accelerometers also extends to canine studies, in which their scope for monitoring disease and enabling the assessment of behaviour and activity has been investigated (Belda et al 2018; Brown et al 2010; Dow et al 2009), demonstrating the potential of such devices for monitoring parameters from which the health and welfare status of companion animals could be inferred. As such, it is possible that accelerometer-based approaches could be designed to assist in the identification and monitoring of the gait and activity abnormalities associated with OA, perhaps addressing the problem of delayed diagnosis.

Before accelerometers could be used to diagnose and monitor conditions such as OA, extensive validation of the necessary approaches would first be required in both healthy and arthritic individuals. While previous chapters have highlighted the potential for sensor-based methods to monitor canine activity and step count, further validation of their use in both sound and arthritic dogs is required. This chapter will validate the use of accelerometer-based approaches for monitoring the activity and logging the steps of sound and arthritic dogs, before comparing the energy expenditure and number of steps taken throughout the two minutes of highest recorded activity. Measurement of the specified parameters enabled a test of functional capacity, as described in Chapter 2, to be completed in a two-minute duration, as trialled in human medicine (Brooks et al 2004). This chapter will also identify the differences in energy expenditure observed during the play and controlled walking of sound dogs. Although the collection of such data from arthritic dogs was not ethically permissible, the comparison of activity counts recorded from sound dogs highlighted activity based changes in energy expenditure which may confound those associated with OA, and should therefore be considered when designing automated methods of detection. The aim of this chapter is to explore candidate parameters from accelerometers which could be used in the diagnosis and monitoring of OA.

4.2 Materials and Methods

4.2.1 Ethical Statement

All methods reported throughout this chapter were conducted following approval from Newcastle university's ethical review board (AWERB) Project ID No: ID 967 and ID 1042.

4.2.2 Recruitment - Sound Dogs

A total of 14 pet dogs of varying ages and breeds (Table 4.1) were recruited from the local area for participation in the study. Recruitment materials (Appendix H) were distributed at local dog festivals, as well as among known contacts and internal Newcastle University communication pages. Once owners had registered their interest in the study, they were invited to complete a recruitment survey (Appendix I), including questions featured in the C-BARQ questionnaire (Hsu and Serpell 2003), designed to screen out any individuals who may display aggressive or anxious behaviours which could be exacerbated by participation in the study. Additional exclusion criteria were implemented against dogs with injuries or known gait imparing conditions, other than osteoarthritis.

Table 4.1 The breeds and ages of sound dogs recruited for participation in the study

Dog ID	Type	Age (Years)	Breed
Dog_1	Sound	2	Cocker Spaniel
Dog_2	Sound	5	Labrador
Dog_3	Sound	1.67	Border Collie
Dog_4	Sound	0.5	Border Collie
Dog_5	Sound	3	Cockapoo
Dog_6	Sound	2.58	Spaniel Crossbreed
Dog_7	Sound	3	Miniature Wirehaired Dachshund
Dog_8	Sound	4	Border Collie
Dog_9	Sound	9	Labradoodle
Dog_10	Sound	8	Border Terrier
Dog_11	Sound	1.5	Whippet
Dog_12	Sound	2	Cocker Spaniel
Dog_13	Sound	1.25	Rhodesian Ridgeback
Dog_14	Sound	2	Norfolk Terrier

4.2.3 Data Collection – Sound Dogs

Data collection took place at the gait lab facility based in the CDIAL building at Newcastle University's Cockle Park Farm. Data for each dog was collected during one single visit, at a pre-agreed time, during which dogs remained under the supervision of their owner. Once in the gait lab, dogs were allowed to acclimatise to the room, off-leash, for a duration of five minutes. During this time, the protocol was discussed with the owner, and consent forms were completed. After the short acclimatisation period, the study took place in two stages, whereby stage one focussed on play, and stage two focussed on locomotion.

4.2.4 Stage One - Play

Stage one sought to record activity data and vocalisations from dogs during play. To do this, dogs were encouraged to complete two rounds of play, one of which was with their owner, and the other was with a researcher unknown to the individual. During each round, play took place in three bouts, unstructured play, tug of war, and fetch. While each bout of play took place in the same order for each dog, rounds took place depending on the dog's perceived confidence, whereby dogs considered to be confident played first with the unknown researcher, while more timid individuals completed the first round of play with their owner.

To enable the recording of activity data, an Axivity AX6 accelerometer and two GoPro Hero 9 cameras were used. The accelerometer and cameras were synchronised using a sequence of five claps, whereby a researcher held the accelerometer in their hand, before clapping five times in front of the cameras. The accelerometer was then placed on the dog, this was done by attaching the device to a lightweight nylon collar using a cohesive vetwrap bandage, which was worn in addition to the dogs own collar. To enable the recording of vocalisations, dogs were also fitted with a harness, the style of which incorporated a chest strap, to which an audio recording device (AudioMoth) was attached using electricians' tape. The GoPro cameras were then placed at opposite ends of the gait lab room.

To begin each round of play, all individuals vacated the gait lab room, leaving only the owner (or researcher) and the dog. The owner or researcher then played with the dog in three bouts: unstructured play; whereby any form of play, such as tug of war or fetch could take place; tug of war, in which the owner/researcher held an item and encouraged the dog to hold the item and attempt to pull it from their grip; and ball throws, in which a ball would be thrown three successive times, and the dog would be encouraged to retrieve this. The first two bouts took place in three-minute intervals, while the third bout ended as soon as the final ball was retrieved. If dogs did not participate in the prescribed play style, the owner or researcher continued to encourage the dog until the three minutes had elapsed. Once all play bouts were complete, all researchers or owners returned to the room, and the dog was given five minutes downtime, during which they were able to rest. The harness and accelerometer collar were not removed during this interval. Once five minutes had elapsed, the process was repeated for the owner/researcher who had not participated in the previous round. Once the play bouts were complete, all researchers/owners returned to the room once more, and the harness containing the AudioMoth was removed from the dog, while the dog continued to wear the collar containing the accelerometer throughout stage two of the protocol.

4.2.5 Stage Two – Locomotion

Following the collection of activity data during play, dogs were given an additional two minutes to rest, this time was used to explain the subsequent stages of the data collection process to the owner. Once two minutes had elapsed, dogs were fitted with 20 spherical photo reflective motion capture markers, which were applied to palpation points and bony landmarks on the dog's head, back, legs and paws (Figure 4.1), using double sided Sellotape™. The behaviour of dogs was monitored throughout the application of the photo reflective markers, and these were removed from any individuals that expressed discomfort which continued beyond a two-minute acclimatisation period. Photo reflective markers were removed from one individual, Dog_13 (Table 4.1), due to the continuation of discomfort beyond the acclimatisation period, throughout which the individual continuously attempted to remove the markers from their own fur.

Figure 4.1 Positioning of reflective markers on palpation points and bony landmarks on the dog's head, back, legs and paws.

After a short acclimatation period, owners attached their dog's leash to their regular collar, ensuring this did not interfere with the collar containing the Axivity device, before completing 10 return laps of a straight 12-meter walkway. The walkway had a non-slip black vinyl surface, with start and end lines clearly defined using blue tape. Each of the 10 laps consisted of a journey from the defined start and end lines, before making a 180° left turn, and making a return journey adjacent to the defined walkway. Throughout each lap, owners were instructed to walk to the left-hand side of their dog, at a pace self-selected by the dog, offering food and vocal based positive reinforcement throughout. The dog's activity was recorded during each lap using the collar mounted accelerometer, as well as the two GoPro cameras which were positioned at the start and end points of the walkway. A series of 16 wall mounted Qualysis cameras, consisting of 12 Oqus and 4 Miqus devices were also used to capture kinematic data in conjunction with the photo reflective markers. Upon completion of the 10 laps, reflective markers were extracted using a wide toothed comb, and collar-based accelerometer was removed. Five synchronisation claps of the accelerometer were completed before GoPro recording ceased. Of the 14 dogs, one dog (Dog_14) completed the 10 laps without a leash, while Dog_4 and Dog_7 completed just seven and nine laps of the walkway respectively.

4.2.6 Recruitment – Arthritic Dogs

A total of five pet dogs of varying ages and breeds (Table 4.2), with a confirmed diagnosis of osteoarthritis were recruited from the local area for participation in the study.

Table 4.2. The age, breed and LOAD score of arthritic dogs recruited to the study

Dog ID	Type	Age (Years)	Breed	LOAD Score
OA_1	OA	17	Crossbreed	14
OA_2	OA	13	Labradoodle, Toy Poodle Crossbreed	8
OA_3	OA	7.5	Yorkshire Terrier, Papillon Crossbreed	17
OA_4	OA	12	Spaniel, Border Collie Crossbreed	25
OA_5	OA	4	Labrador, Border Collie Crossbreed	13

As with the recruitment of sound dogs, this was done by distributing recruitment materials (Appendix J) at local dog festivals, as well as among known contacts and internal university communication pages. Upon registering interest, owners completed a recruitment survey (Appendix I), including questions featured in the C-BARQ questionnaire (Hsu and Serpell 2003) implemented to screen out any individuals who may display aggressive or anxious behaviours which could be exacerbated by participation in the study. Owners were also asked to complete a Liverpool Osteoarthritis in Dogs (LOAD) questionnaire (Appendix K), to ascertain the severity of their dog's condition, in the format of a LOAD score, and individuals whose osteoarthritis was staged as severe were excluded from participating in the study.

4.2.7 Data Collection – Arthritic Dogs

The activity of five arthritic dogs was recorded during their routine walk, using an Axivity AX6 accelerometer, and a single GoPro Hero 9 camera. To do this, a researcher joined each dog and their owner at the start point of their regular walking route. The dog was given five minutes to acclimatise to the presence of the researcher, during which time the protocol was discussed with the owner, and consent forms were completed. An additional LOAD questionnaire was also completed if the owner felt the severity of their dog's condition had changed since their initial registration.

Following the acclimatisation period, the accelerometer, attached to a lightweight nylon collar using a cohesive vet wrap bandage, was synchronised with a single GoPro Hero 9 camera, by performing five claps while holding the Axivity device. The collar mounted accelerometer was then placed on the dog, in addition to their regular collar, ensuring no leash was attached to the novel collar. Owners were then instructed to walk their dog at their dog's self-selected pace, following their typical route. Researchers walked adjacent to the dog, capturing video footage on the GoPro camera, ensuring the entire dog, including all four limbs, were visible. Once 30 minutes had elapsed, or the walk had reached its typical endpoint (depending on which event occurred earliest), the collar was removed from the dog, and an additional five synchronisation claps were performed in front of the GoPro camera, after which recording ceased.

4.2.8 Data Processing

The initial stages of data processing were consistent for both sound and arthritic dogs. First, GoPro video chapters were stitched together to form one continuous video clip, using ReelSteady Joiner v.1.3.2, before re-encoding each video file to remove audio content, using VLC media player Version 3.0.20. Next, raw accelerometer data files were resampled using the omconvert conversion program within the OMGUI software, to ensure data were sampled evenly at a rate of 100Hz. Resampled accelerometer data were then imported to RStudio – 4.3.0, where the date and time stamps were converted to a numeric format, beginning at zero, and increasing in increments of 0.01 between each sample point. Column headers were then removed to ensure readability in subsequent software.

4.2.9 Data Processing – Sound Dogs

For each of the 14 sound dogs, resampled accelerometer data and supporting video footage was imported to ELAN (Version 6.7). First, video and accelerometer data were synchronised by identifying the frame in which the first in the series of five claps commenced, before pairing this with a characteristic peak in the Z axis of the accelerometer data. It was not possible to synchronise the data obtained from two dogs (Dog_6 and Dog_8), leading to the exclusion of data recorded from these individuals from subsequent processing and analysis.

Next, labels were used to identify the start and end times of each play bout completed with both the owner and the unfamiliar researcher. The start and end times of each walking lap were also identified, and the number of steps completed by each forelimb was manually counted and recorded. Throughout the labelling process, a small degree of drift was observed in the data, resulting in the loss of synchronisation between the video and resampled accelerometer signal. To ascertain the degree of drift between the two data sources, the first frame in the second series of five claps was identified, before isolating the characteristic peak in the Z axis of the corresponding accelerometer data and recording the time difference between the two events.

Resampled accelerometer data were then imported into RStudio, where play bouts and walking laps were extracted based upon the recorded start and end times. To compensate for data drift, a time buffer, representing the disparity observed between the video and accelerometer data, was added to the start and end times for each extracted section. Next, individual play bouts and walking laps were stitched together, creating two data frames per dog, whereby the first contained all acceleration data collected during play, while the second comprised of data recorded during lap walking.

To assess the intensity of each activity (play and walking), the 'actilifecounts' package was used to generate activity counts from the X, Y and Z axis of the resampled accelerometer data frames at a rate of one count per minute. In doing so, the vector magnitude (VM) was automatically calculated from the X, Y and Z axes, generating an integrated axis, from which activity intensity across all planes of movement could be inferred. Next, the two minutes of highest continuous activity was extracted from the play and walking data frames. This was achieved by applying a rolling mean to the integrated axis of each data frame before selecting the two-minute window with the highest mean activity count and recording the reported values.

Next, the reliability to which the pedometer algorithm, defined in Chapter 1, could predict the step count of sound dogs, walking in a controlled environment, was assessed. To do this, the pedometer algorithm was applied to the data frame containing acceleration data from dogs completing lap walking, producing an initial and filtered step count, each of which were recorded alongside the manual step counts obtained during the video annotation stages of data processing. The five dogs for which steps were predicted most reliably, whereby the difference in the predicted step count and the manual count was less than 100 steps, were then selected. For each of the selected dogs, the pedometer algorithm was applied to the two minutes of highest continuous activity identified during lap walking. And the resulting step counts (both initial and filtered) were stored for direct comparison with the arthritic cohort.

Due to time constraints, kinematic data collected using the motion capture system could not be processed or analysed.

4.2.10 Data Processing – Arthritic Dogs

For each of the arthritic cohort, resampled accelerometer data and GoPro video footage was read into ELAN, where the two data sources were synchronised by pairing the first video frame in the series of five claps with the characteristic peak in the Z axis of the accelerometer data. Next, labels were used to identify sections of video where the entire dog, including all four limbs, were visible, before manually counting and recording the number of steps completed by the thoracic forelimbs during each section. As with the sound cohort, a small degree of drift was observed between the video and accelerometer data, leading to a loss of synchronisation between the two sources. To establish the extent of the data drift, the first frame in the second series of five claps was identified in the video file, before isolating the associated peak in the Z axis of the accelerometer data and recording the time disparity between the two events.

Resampled accelerometer data were then imported to RStudio, whereby all instances of walking, in which all four limbs were visible, were extracted based upon the recorded start and end times of each section. To compensate for the data drift, a time buffer, equal to the time disparity observed between the two data sources, was added to the start and end points of each extracted section. Individual sections were then stitched together in chronological order, creating a single data frame containing all extracted sections of walking.

After extracting and merging all relevant sections of resampled accelerometer data, an inference of energy expenditure during walking was obtained by calculating activity counts. To do this, the 'actilifecounts' package was used to generate activity counts, based on a sampling frequency of 100Hz, and a 60 second epoch, before calculating the VM, from which activity intensity across the X, Y, and Z axis could be indicated. The two minutes of highest continuous activity was then identified from the combined data frame, by applying a rolling mean to the integrated axis, before selecting and recording the start and end times of the two minutes represented by the highest mean value, as well as the mean activity counts generated for the selected window.

Next, the reliability of the pedometer algorithm (described in chapter 1) when predicting the step count of arthritic dogs was investigated. To do this, the defined algorithm was applied to the data frame containing all walking data for which steps had been manually counted, producing two step count values, an initial step count, as well as filtered count, (whereby irregular steps and shuffles were removed), each of which were recorded. The pedometer algorithm was then applied to the two minutes of highest continuous activity, previously identified from the merged data frame. The resulting step counts, including both the initial count and the filtered count, were then stored for a direct comparison with the sound cohort.

4.2.11 Statistical analysis

Step count was considered in two categories, including the initial count, whereby genuine step candidates and irregular steps were recorded, as well as the filtered count, whereby all irregular steps, such as shuffles, were removed. R^2 was then used to explore the relationship between the manually counted steps, and the two step count categories predicted by the pedometer algorithm, for both the sound and arthritic cohorts.

Next, the pedometer step counts predicted from the two minutes of highest continuous activity recorded during walking for both arthritic dogs, and the five selected sound dogs, were explored using descriptive statistics. As a large degree of variation both within and between groups was identified for both initial and filtered step counts, the use of scaling and re-centring was made necessary. To do this, the 'scaler' function within R's 'coop' package was used to first recentre initial and filtered step counts, by subtracting column means from all datapoints, before scaling, via the division of centred datapoints by their standard deviations.

The relationship between OA, age and the two step count categories were then investigated using linear regression models. In the first model, OA was included as the independent variable, before entering the initial step count as the dependent variable. Models were then repeated to include age as an independent variable, before including both age and OA. This process was then repeated to include the filtered step count as an outcome variable. Data were then subset to include the scaled and recentred initial and filtered step counts of the arthritic dogs only. Next, an additional exploratory linear regression model was created, including age as an independent variable, before entering the initial step count of arthritic dogs as a dependent variable. The model was then repeated to include LOAD score as an independent variable. The process was carried out sequentially to enable the consideration of age and LOAD score as independent variables, without the creation of a multivariate model.

Models were then repeated to include the filtered step count of arthritic dogs as the outcome variable.

Descriptive statistics were used to explore the mean activity counts of sound and arthritic dogs, during the two minutes of highest continuous activity observed during walking, as well as the mean activity counts of sound dogs, during the two minutes of highest continuous activity observed during play. As a large degree of variation in the mean activity counts was observed within and between groups, for both walking and playing, the use of scaling and recentring was once more implemented.

Next, the relationship between mean activity counts (generated from walking data), OA and age was investigated, using additional linear regression models. The first model included OA as the independent variable, before selecting mean activity counts (obtained from walking data) as the dependent variable. The model was then repeated to include age as an independent variable before an additional model included both OA and age.

The final stage of data analysis involved exploring the relationship between activity type and the mean activity counts of sound dogs, calculated from the two minutes of highest continuous activity observed during walking and playing. To do this, data were first subset to include only sound individuals. Next, a linear mixed effects (LME) model was constructed, with mean activity counts specified as an outcome variable, while activity type was included as an independent variable, with dog ID as a random effect. To avoid obtaining a singular fit, the relationship between mean activity counts and activity type were further explored using Bayesian LME models. Mean activity counts were once more entered as the dependent variable, with activity type and dog ID included as independent variables and random effects respectively. An ANOVA test was then conducted to test for significance when comparing the null and alternative models.

4.3 Results

4.3.1 Pedometer Validation

When compared to manually counted steps, the initial step count was overestimated for five sound dogs and underestimated for the remaining seven dogs (Table 4.3). The filtered step count was lower than the initial step count for all but two sound dogs (Dog_5 and Dog_13), resulting in an underestimate for eight dogs, and an overestimate for the remaining four dogs.

While the manually counted steps explained approximately 33% of the variability in the initial step count generated by the pedometer algorithm, (R^2= 0.327), this reduced to 31% when considering the filtered step count (R^2= 0.311). Dogs for whom step count was predicted most reliably by the pedometer algorithm (whereby the difference between the manually counted steps and the initial pedometer steps was less than 100) included Dog_1, Dog_2, Dog_3, Dog_4, and Dog_13. For the five selected dogs, manually counted steps explained approximately 90% and 63% of the variability in the in the initial and filtered pedometer step counts respectively (R^2= 0.899 & 0.634 respectively).

Table 4.3. Summary of steps counted manually, as well as those generated by the pedometer algorithm for sound dogs.

Dog ID	Type	Manually counted steps	Initial pedometer steps	Filtered pedometer steps
Dog_1	Sound	784	792	650
Dog_2		565	590	570
Dog_3		700	791	760
Dog_4		423	356	320
Dog_5		558	456	460
Dog_7		907	681	650
Dog_9		670	907	860
Dog_10		889	669	630
Dog_11		746	538	530
Dog_12		671	493	470
Dog_13		477	552	570
Dog_14		1047	749	730

For arthritic dogs, the initial pedometer step count was overestimated for three dogs and underestimated for the remaining two dogs (Table 4.4). Conversely, the filtered pedometer step count was underestimated for 3 dogs and overestimated for two dogs when compared to the manually obtained step count. The manually counted steps explained approximately 75% of the variability for both the initial pedometer step count, and the filtered pedometer step count (R^2= 0.751 & 0.752 respectively), whereby the filtered step count was marginally more reliable.

Table 4.4. Summary of steps counted manually, as well as those predicted by the pedometer algorithm for arthritic dogs.

Dog ID	Type	Manually counted steps	Initial pedometer steps	Filtered pedometer steps
OA_1	OA	3369	3889	3270
OA_2		3266	4057	3830
OA_3		3771	3259	3080
OA_4		3205	4391	4040
OA_5		1122	1050	960

4.3.2 Mean Pedometer Step Counts

In the two minutes of highest continuous activity observed during walking, the mean values for the initial and filtered pedometer step counts were consistently greater for sound dogs (Table 4.5).

Table 4.5. Mean values for the initial step count and filtered step count, calculated for sound and arthritic dogs during the two minutes of highest continuous activity observed during walking.

	Initial step count (mean)	Filtered Step count (mean)
Sound	333 (±85.30 SD)	282 (±79.50 SD)
OA	275 (±104.34 SD)	240 (±119.58 SD)

The within group variation was largest for arthritic dogs, with the largest degree of variation observed for the initial step count (Figure 4.2). A reasonable degree of variation was also observed between the two groups, for both step count categories, with the greatest difference found in the initial step count.

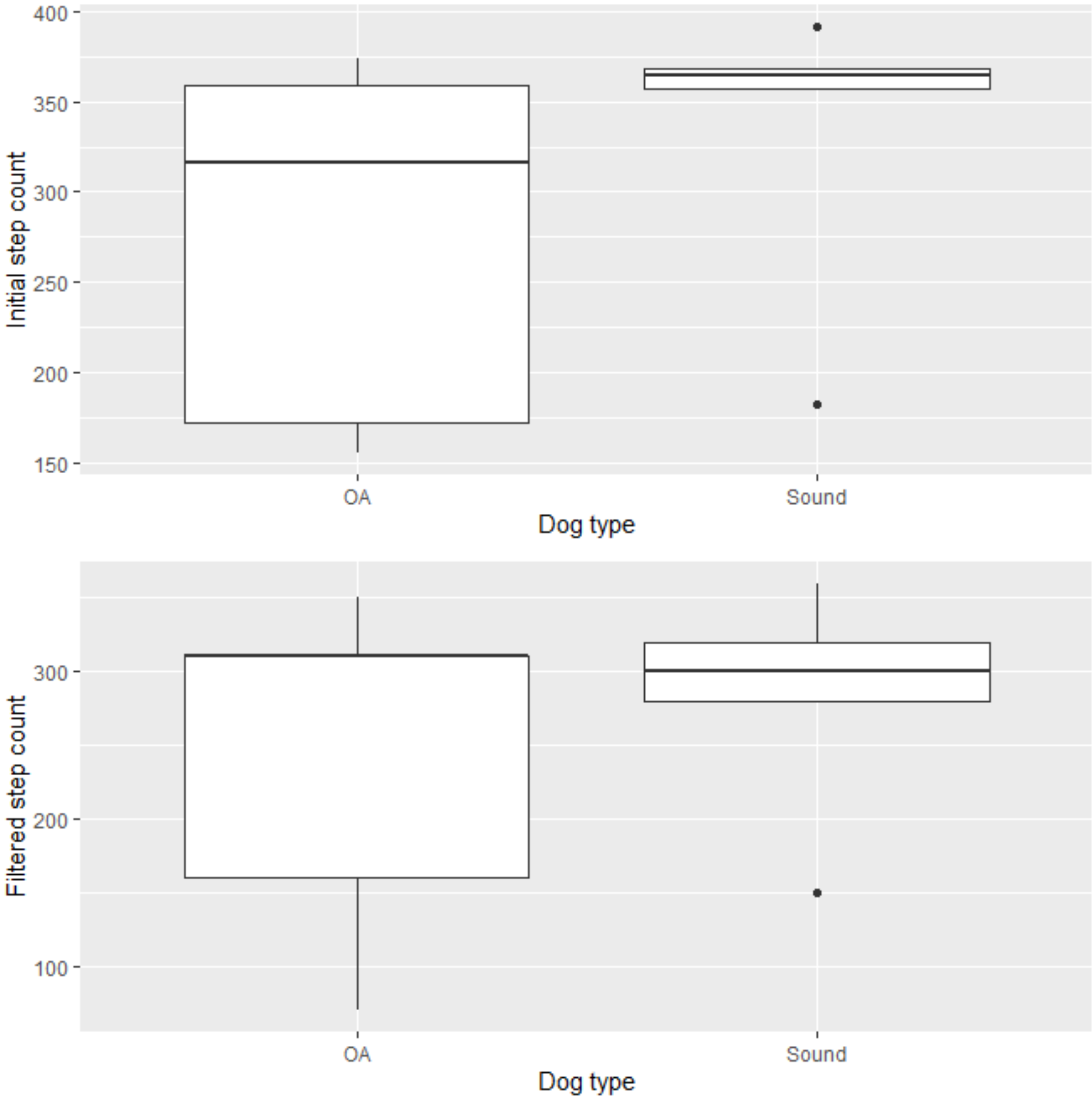


Figure 4.2. The degree of variation in the two step count categories (top: initial step count and bottom: filtered step count), generated by the pedometer algorithm for sound and arthritic dogs.

4.3.3 The Relationship between osteoarthritis, age, and the two step count categories

No significant association was observed between the step count categories and age, with P>0.05 in all models (Table 4.6). Similarly, no significant association was detected between the step count categories and a confirmed diagnosis of OA.

Table 4.6. Summary of linear regression models exploring the relationship between age, OA, and the two step count categories.

Independent variable	Dependent variable	Estimate	P value	T value	Standard error
OA	Initial step count	0.607	0.367	0.956	0.636
Age	Initial step count	-0.094	0.104	-1.832	0.051
OA and Age	Initial step count	-0.133 (Age) -0.540 (OA)	0.171 (Age) 0.590 (OA)	-1.525 (Age) -0.565 (OA)	0.087 (Age) 0.955 (OA)
OA	Filtered step count	0.428	0.531	0.654	0.654
Age	Filtered step count	-0.092	0.115	-1.771	0.052
OA and Age	Filtered step count	-0.161 (Age) -0.962 (OA)	0.096 (Age) 0.328 (OA)	-1.925 (Age) -1.050 (OA)	0.084 (Age) 0.917 (OA)

4.3.4. The relationship between osteoarthritis severity, age, and the two step count categories

When included in the regression model as a single independent variable, no significant relationship was identified between LOAD score (an indicator of osteoarthritis severity) and the two step count categories generated by the pedometer algorithm, (P>0.05) (Table 4.7).

Table 4.7. Summary of linear regression models exploring the relationship between age, osteoarthritis severity, and the two step count categories. Significant results are highlighted using an asterisk (*) in the P value column.

Independent variable	Dependent variable	Estimate	P value	T value	Standard error
LOAD score	Initial step count	0.095	0.287	1.292	0.074
Age	Initial step count	-0.158	0.106	-2.286	0.069
LOAD score	Filtered step count	0.072	0.447	0.873	0.082
Age	Filtered step count	-0.175	0.049 *	-3.219	0.054

Similarly, no significant relationship was observed between age and the initial step count (P>0.05), when included as the only independent variable in the regression model. Despite this, a significant effect was detected between age and the filtered step count (P=0.049), whereby an increased number of steps was observed from older dogs (Figure 4.3).

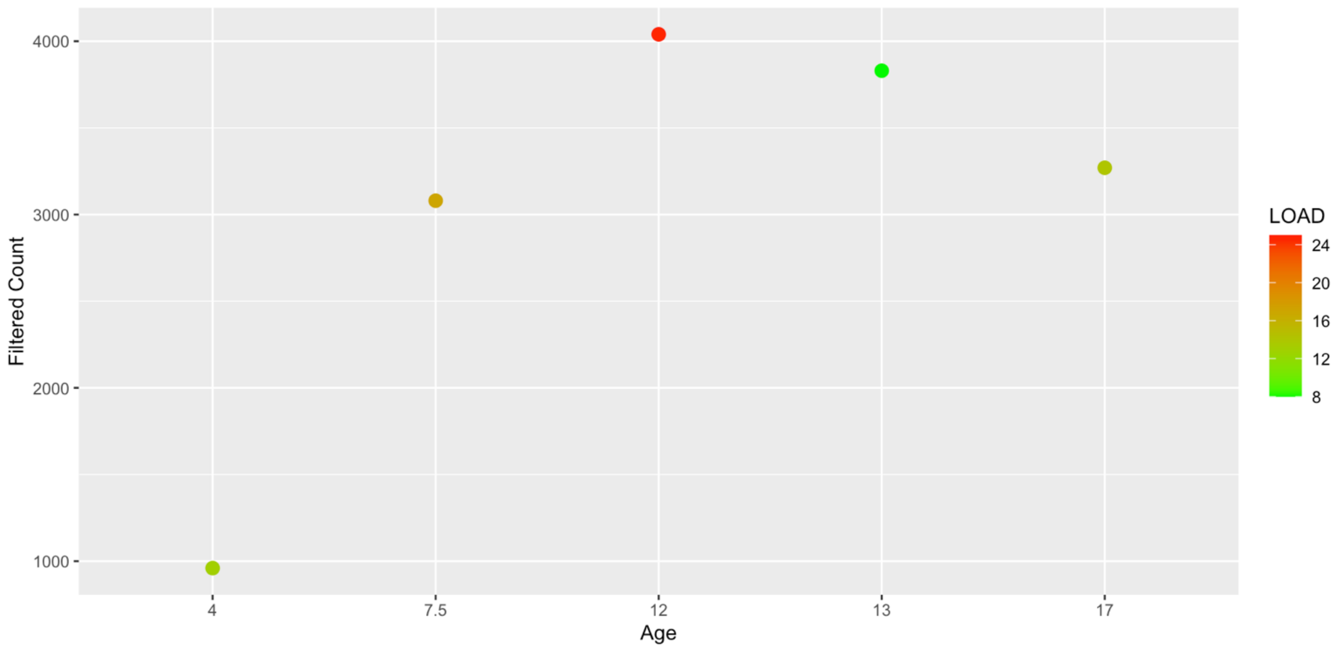


Figure 4.3. The relationship between the filtered step count, age and osteoarthritis severity, observed in arthritic dogs.

4.3.5 Mean activity counts

For Sound dogs, the mean activity counts representing the two minutes of highest continuous activity observed during play is greater than those calculated during the two minutes of highest continuous activity observed during walking (Table 4.8 &Figure 4.4).

Table 4.8. Mean values for mean activity counts calculated from the two minutes of highest continuous activity observed during walking and playing.

	Mean activity count - play	Mean activity count - walking
Sound	10068.43 (±2142.46 SD)	5867.83 (±1567.51 SD)
OA	NA	2438.49 (±3288.73 SD)

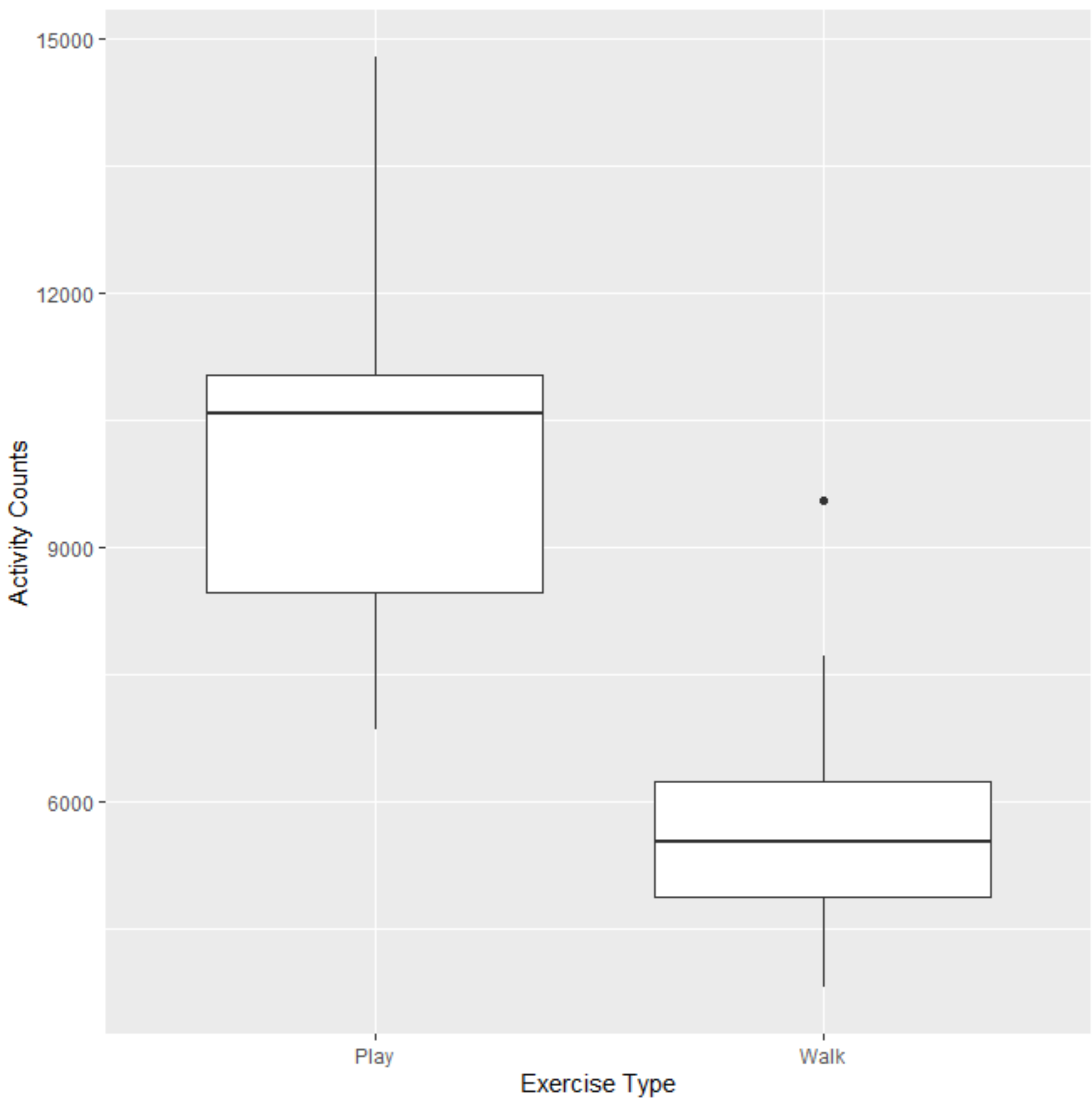


Figure 4.4. The degree of variation in the mean activity counts generated in the two minutes of highest continuous activity observed from sound dogs during walking and playing.

While no play data were recorded from the arthritic cohort, the mean activity counts calculated from the two minutes of highest continuous activity while walking was less than those calculated for their sound counterparts (Figure 4.5). Despite this, the variation in mean activity counts was highest for arthritic dogs.

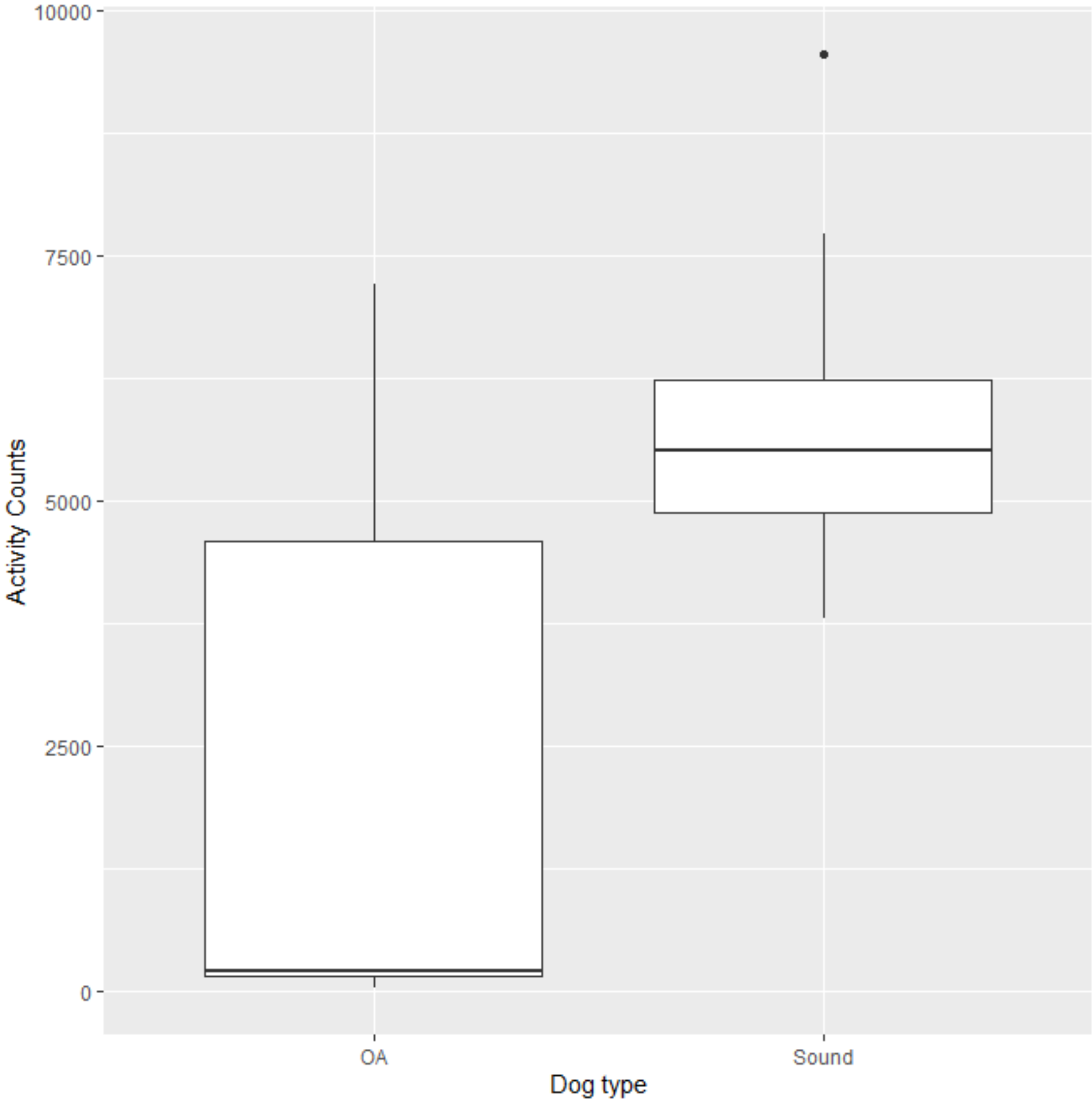


Figure 4.5. The degree of variation in the mean activity counts generated in the two minutes of highest continuous activity observed from sound and arthritic dogs during walking.

4.3.6 The relationship between mean activity counts, osteoarthritis, and age

A significant association was observed between osteoarthritis and the mean activity counts extracted from the two minutes of highest continuous activity recorded during walking (P=0.0094) (Table 4.9, Figure 4.6), whereby the mean activity counts of arthritic dogs were lower than their sound counterparts. No significant effects were observed between age and activity counts (P >0.05) across all models. Associations between OA and mean activity counts increased when age was included as a second independent variable in the linear regression model (P=0.0087).

Table 4.9. Summary of linear regression models exploring the relationship between age, osteoarthritis, and mean activity counts. Significant results are highlighted using an asterisk (*) in the P value column.

Independent variable	Dependent variable	Estimate	P value	T value	Standard error
OA	Mean activity counts	1.297	0.0094 *	2.976	0.436
Age	Mean activity counts	-0.053	0.317	-1.035	0.051
Age and OA	Mean activity counts	0.077 (Age) 1.871 (OA)	0.215 (Age) 0.009 (OA) *	1.299 (Age) 3.047 (OA)	0.059 (Age) 0.614 (OA)

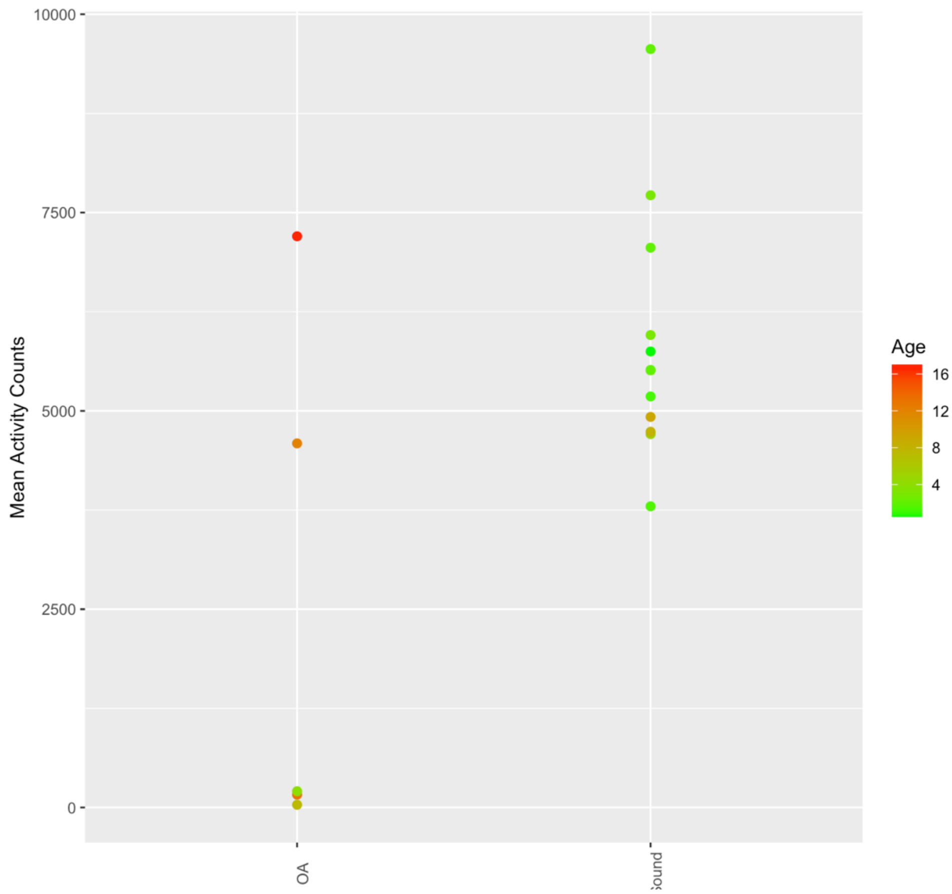


Figure 4.6. The relationship between mean activity counts, osteoarthritis, and age.

4.3.7 The relationship between activity counts and activity type, using a Bayesian mixed effects model

Comparison of the Bayesian LME models supported the use of the alternative model, suggesting that the relationship between activity type and mean activity counts was significant (P<0.01) (Table 4.10).

Table 4.10. Summary of Bayesian Linear Mixed Effects model, exploring the relationship between activity type and mean activity counts observed from sound dogs.

Independent variable	Dependent Variable	Random Effect	Estimate	Standard error	T Value	Anova test P value
Activity type	Mean activity count	Dog ID	-1.488	0.246	-6.042	<0.001
Activity type	Mean activity count (null model)	Dog ID	-3.21E-16	2.24E-01	0	

4.4 Discussion

We collected the activity data of 14 sound dogs undertaking play and lap walking in a controlled environment, using an accelerometer and video camera. Further activity data were also collected from a cohort of five arthritic dogs, who undertook walking in a non-controlled environment. From the activity data of sound dogs, forelimb steps were manually counted from lap walking, before identifying the two minutes of highest continuous activity observed both during walking and playing, before using the step detection algorithm, defined in chapter 1, to predict initial and filtered step counts from the walking window. Manual forelimb step counts were also obtained from arthritic dogs, before the two minutes of highest continuous activity was identified from the walking data, and the pedometer algorithm was used to generate initial and filtered step counts.

Manual step counts were first used to assess the ability of the pedometer algorithm, defined in chapter 1, to reliably predict the forelimbs steps of sound and arthritic dogs. For the sound cohort, the reliability of the initial step counts predicted by the pedometer algorithm was low, however associations with the manual step count increased slightly when considering the filtered step count. Associations between the manual step count and the two pedometer counts then increased to a reasonable degree of reliability when considering only the five sound dogs, for whom predicted steps were within 100 counts of the manually obtained step count, with associations highest for the initial step count when compared to the filtered count. Despite this, associations remained lower than those observed during the validation exercise of chapter 1. When considering the arthritic cohort, steps were predicted with reduced reliability when compared with the five aforementioned sound dogs. Despite this, a relatively high association was observed between manual obtained step counts, and the initial step count predicted by the pedometer algorithm, with associations increasing for the filtered step count.

The number of pedometer generated steps predicted during the two minutes of highest continuous activity, observed during walking, was then compared between the sound and arthritic cohorts. While the mean values for the initial and filtered step counts were greater for sound dogs, this association was not significant, with no further relationship identified between step counts and age. When considering arthritic individuals only, exploratory analyses suggest that the initial step counts were not associated with age, nor LOAD score when including each of these variables in the regression model separately. Although a relationship was observed between age and the filtered step counts of arthritic dogs, this was based on a model of only five data points, while a larger sample size would be required to increase statistical power.

The mean activity counts generated for both sound and arthritic dogs, during the two minutes of highest continuous activity observed during walking, were then compared. Associations were observed between activity counts and a confirmed diagnosis of OA, with interactions between activity counts and OA strengthening when including age as an additional independent variable in the regression model. Despite this, no associations were identified between age and mean activity counts when this relationship was explored independently. Next, subsetting of the data to include only sound dogs allowed for a comparison of mean activity counts extracted during walking, with those observed during play, enabling the identification of associations between activity type and mean activity counts.

It was important to include a validation exercise as the first stage in data analysis, in order to gauge the reliability to which the pedometer algorithm could predict steps for both sound and arthritic dogs. The need for validation was emphasised further when considering the small validation dataset used during chapter 1, whereby a small range of breeds were sampled, with no representation from dogs with a diagnosed gait impairing condition. While the additional validation exercise encompassed a larger sample size, including a range of ages, conformations and severity of gait impairing conditions (OA), the outcome of this suggested that the pedometer algorithm was performing at a lower level of reliability than previously expected. When considering the cohort of sound dogs, the reduction in reliability could be due to a range of factors including the conformation of breeds sampled, whereby two chondrodystrophic breeds were included in the sound dataset, a Miniature Wirehaired Dachshund, and a Norfolk Terrier (Table 4.1). Chondrodystrophy results in conformational changes, including disproportionately short limbs (Smolders et al 2013), which may influence an individual’s posture and gait. As the pedometer algorithm was developed and validated with clinically sound dogs, it is possible that the underestimation of steps for the associated dogs may be due to breed related gait abnormalities, perhaps accounting for some of the observed unreliability. Further deviations to normal gait could be explained by the potential inclusion of dogs with undiagnosed gait impairing conditions, such as OA, a factor which cannot be dismissed due to the fact that LOAD scores were not obtained for sound individuals. When considering the potential unreliability caused by gait abnormalities, it is important to also acknowledge the possible impact of gait monitoring equipment, particularly photo-reflective markers. Although dogs were given time to acclimatise to the application of markers, it is reasonable to consider that the presence of such novel objects may have altered the dog's normal gait, particularly when walking in an unfamiliar environment. Similar effects of instrumentation were noted by Ladha et al (2017). Additional causes for the observed unreliability could include potential human error when manually counting steps, as well as the level of drift observed between the accelerometer and video data. Although a time buffer was implemented in response to the observed time disparity between the two data sources, it is possible that the inclusion of additional data, from which steps were not manually counted, could account for the overestimation of initial and filtered step counts observed for five and four sound dogs respectively.

Despite the level of unreliability observed in the predicted step counts of sound dogs when studying the entire cohort, consideration of individual dogs highlighted five instances in which steps were predicted with a relatively high degree of reliability, whereby initial steps were within 100 counts of the manually recorded steps. While it is unclear why reliability improved for the five sound dogs (Dog_1, Dog_2, Dog_3, Dog_4, and Dog_13), this was possibly due to a range of factors including a lower degree of human error when manually counting steps, as well as improved acclimatisation to the presence of reflective markers, perhaps limiting the extent to which the dog's normal gait was impacted. A final factor perhaps influencing the reliability of step prediction could be that no chondrodystrophic breeds were included among the five selected dogs. Although the pedometer algorithm performed poorly beyond the two chondrodystrophic individuals, the step counts predicted for these dogs (Dog_7 and Dog_14) were the least reliable. As such, the lack of chondrodystrophic breeds among the five selected dogs possibly eliminated the effect of associated gait abnormalities, improving the percieved reliability.

Although steps were predicted with a reasonable degree of reliability for arthritic dogs, there was still a large degree of variation in the predicted step count, which could not be predicted by the manually obtained count. It is possible that the degree of unreliability was observed in the predicted steps of arthritic dogs due to a range of factors, the first of which being that the step detection algorithm was developed and validated using clinically sound dogs (Ladha et al 2018). As OA can cause lameness (Anderson et al 2020), it is possible that affected individuals will demonstrate different patterns of movement when compared to their sound counterparts, whereby such deviations in gait may cause steps to be overlooked or artificially generated by the pedometer algorithm. Additional deviations in gait may have arisen from locomoting over a range of terrains, including smooth pavement and hilly woodland, perhaps further confounding the algorithm's ability to reliably identify steps. This was previously considered in human gait analysis, whereby Cole et al (2014) suggested that the most appropriate method of accounting for gravitational acceleration when estimating step count from accelerometer data depended on the nature of the surface upon which the participant was walking, a factor which may also be applicable to canine gait analysis. Final causes for the lack of reliability when predicting the step count of arthritic dogs are shared with the sound cohort, including potential human error when manually counting steps, as well as the possible impacts of data drift and stitching.

While the filtered step counts of arthritic dogs had a similar degree of unreliability observed in the initial step count, a larger degree of variation in this count could be explained by the manually counted steps, which were not counted blind to the condition of the dog. The increased reliability of the filtered step count for arthritic individuals may be due to screening against irregular steps and shuffles, perhaps ensuring that events such as limping did not contribute to the predicted count.

Once the relibaility of the pedometer algorithm was assessed, it was important to apply this to an equal time duration for all dogs. As the recorded walking duration of arthritic dogs ranged from 10 to 30 minutes, while lap walking took sound dogs approximately three minutes to complete, it is reasonable to consider that arthritic dogs had more scope to generate higher step counts, thus a reliable comparison between the two groups required uniformity in the sampled time duration. As some sound dogs completed the defined number of laps in under three minutes, a two-minute sample time duration was selected for both sound and arthritic dogs.

When selecting the two-minute window from which to extract steps for both sound and arthritic dogs, it was important to consider at which stage of the walk the highest levels of activity and thus step counts were likely to occur. While OA symptoms such as inactivity stiffness may lead to a reduction in activity at the beginning of a walk (Pettitt and German 2015), addiitonal factors such as the use of a leash could also influence levels of activity and subsequent step counts at varying stages of a walk, depending on the routine of the owner. With this in mind, it was considered that steps for both sound and arthritic dogs should be extracted from the two-minute window represented by the highest mean activity counts. This was based on the assumption that dogs would be in motion at this time, increasing the likelihood that steps would be detected. Additionally, by selecting the two-minute window with the highest mean activity count, it was made more likely that the maximum number of steps achievable within a two-minute timeframe would be extracted, highlighting the capabilities of each individual, resulting in a more objective approach than randomly selecting the sampled window.

Upon selecting the relevant two-minute windows from which step counts would be extracted, the pedometer algorithm was applied. While this occurred for all dogs in the arthritic cohort, steps were only generated for the five sound dogs for which step count was predicted most reliably during the validation exercise. Although a large proportion of the sound cohort were excluded, it was important for the pedometer generated steps to be as reliable as possible, to improve the reliability of observations made when comparing the predicted counts of sound and arthritic dogs. While the inclusion of just five sound dogs at this stage of the study allowed for a matched sample size between the two groups, a larger sample size would have made results more representative and statistically robust.

No relationship was detected between osteoarthritis, age and the two step count categories generated by the pedometer algorithm. When considering potential reasons for this, thought should first be given to the study design. Although step count was recorded from the two minutes of highest continuous activity observed during walking for both sound and arthritic dogs, sound dogs had participated in six separate bouts of play before completing the recorded lap walks, suggesting that the step count of sound dogs may have been impacted by fatigue. In addition to this, reflective markers were applied only to sound dogs. While the presence of novel markers may have altered the gait of sound dogs, perhaps increasing the rate that steps were overlooked or falsely generated, such markers were not applied to the arthritic cohort, meaning the observed effects were not consistent between the groups. A final potential cause directly linked to the study design is the fact that arthritic dogs were walked outside, following a familiar route, across a range of terrains, while sound dogs were walked in an unfamiliar setting, across a uniform surface, in a repetitive manner. As an outdoor walk offers a greater degree of variability in sights, sounds and smells, it is possible that such walks generate a higher level of excitement, when compared with indoor walking. As excitement may impact the pace of the individual, as described by Craigon et al (2017), it is possible that the difference in walking location may have influenced the perceived relationship between step counts, OA and age. Additional factors which may have influenced the number of pedometer generated steps is the potential inclusion of undiagnosed OA in the sound group, as well as the inclusion of potentially well managed individuals within the arthritic cohort, perhaps overinflating or capping the number of steps observed. This factor could be further exacerbated by the lack of individuals with higher levels of OA severity within the arthritic group, whereby only one individual fell within the severe catergory, which required a LOAD score of 21-30 (University of Liverpool 2017). To overcome such issues, a before and after study design could be implemented, in which dogs are sampled longitudinally before and after a diagnosis of OA, allowing for variation between dogs, and accounting for the intermittent nature of OA symptoms described by Belshaw et al (2020a). Such a study should sample all dogs in the same environment, with repeated measures enabling outdoor and indoor walking.

Next, the relationship between osteoarthritis severity, age and the two step count categories was explored, using LOAD score as a proxy for OA severity. As LOAD score was recorded from the arthritic cohort only, data were first subset to include only the individuals from this group. Although no associations were identified between the initial step count, age and LOAD score, associations were detected between age and the filtered step count, whereby the filtered step count generally increased with the age of the individual. Such observations may suggest that the number of irregular steps and shuffles taken by an arthritic dog decrease with age, with such steps being identified and excluded by the pedometer algorithm, resulting in an increased number of steps being included in the filtered count. While the observed interaction may be due to the nature of OA, whereby age is a recognised risk factor (Anderson et al 2020), no such association was observed between the filtered count and LOAD score, an indicator of osteoarthritis severity. Despite this, when visualising the association between age and the filtered step count (Figure 4.5), the LOAD score of sampled individuals generally increased with age, suggesting there may be a degree of corellation between the two variables. Although the observed relationship may be due to the subjective nature of clinical metrology instruments (Alves et al 2022), suggesting that age may be a competitive predictor of OA severity, alternative justification for the relationship could involve the restriction of exercise enforced by the owner, whereby owners may may consider age and illness to be obstructive to dog walking (Belshaw et al 2020b). The provision of low intensity walking with enforced breaks could reduce the number of steps taken outside of the frequency expected by the pedometer algorithm, increasing the number of steps included in the filtered count. Despite this, such assumptions must be treated with caution due to the potential corellation between age and OA severity, as well as the innacuarcy of the pedometer generated step counts, and the small sample size. Small sample sizes were observed not only in the number of arthritic dogs, but also in the number of sound dogs occupying older age brackets, whereby recruitment was perhaps limited due to the prevalence of OA in approximately 80% of dogs exceeding the age of eight years (Anderson et al 2018). To improve confidence in the observed interactions, a larger sample size, incorporating a broad range of ages and condition severity would be required.

Interactions were observed between OA and mean activity counts, whereby lower counts were observed from arthritic individuals. Such interactions suggest that arthritic dogs expend less energy during walking when compared to their sound counterparts, Despite this, descriptive statistics highlighted a large degree of variation in mean activity counts within the osteoarthritic group, with some individual counts falling within the sedentary classification (Yam et al 2011). While it could be argued that such counts are due to the inclusion of a time buffer, in response to the observed data drift, whereby the extended windows may have included instances of static posture, the pedometer algorithm detected steps from the very same windows, suggesting that the affected dogs were not in fact sedentary. While it is possible that arthritic dogs may require revised activity thresholds, this assumption would necessitate further investigation, with the use of activity data and supporting video footage, collected from a large sample of arthritic dogs, with a broad range of condition severity.

While no associations were observed between mean activity counts and age, interactions between mean activity counts and OA strengthened when including age as an additional independent variable, highlighting correlation between the two variables. As no further association was identified with LOAD score or age, it could be suggested that the observed relationship is due entirely to OA, for which age is a known predictor.

Next, mean activity counts were used to better understand the difference in energy expenditure with changing activities. Although the protocol implemented in chapter one involved the extraction of steps from the six minutes of highest continuous activity, no supporting video footage was collected. As activities such as play could result in higher mean activity counts than those such as walking, it is possible that application of the pedometer algorithm to a six-minute window containing play data may have resulted in the generation step counts which were not truly representative of the individual’s capabilities. It is therefore important to understand the relationship between activity counts and activity type before collecting sensor-based data without supporting video footage. Furthermore, the increased activity counts observed during play when compared to walking suggests that activity counts could be used as a measurable parameter for identifying play behaviour.

Associations were observed between activity counts and activity type, with mean activity counts increasing during play when compared to walking, suggesting that a greater degree of energy expenditure takes place during play. Despite this, the protocol dictated that play took place prior to the completion of recorded laps for all sound dogs, meaning that the perceived interactions may be due to fatigue. Although dogs were given breaks between each stage of the protocol, further investigation into the impact of fatigue on the observed relationship would be reasonable, whereby the order of play and walking activities should be randomly allocated between the dogs, with extended breaks in between each activity.

Further limitations of the study begin with the fact that the pedometer algorithm performed to a limited degree of reliability for both sound and arthritic dogs. While it is unclear why the algorithm declined in performance when compared to its use in Chapter one, it is possible that level of drift observed between the video and accelerometer data sources, as well as the stitching together of accelerometer data were among the contributing factors. To ensure that step counts generated by the pedometer algorithm are reliable, further validation would be required, in which the pedometer algorithm should be applied to continuous data, recorded in short bursts, to avoid the potential for drift, as well as the need for data stitching. To ensure the algorithm would be applicable to a range of dogs, including those with gait abnormalities, further features of an additional validation exercise should include an increased sample size, encompassing a broad range of conformations, ages, and stages of osteoarthritis severity.

Additional study limitations involve the limited sample size of sound and arthritic dogs, whereby the cohort of sound dogs was further reduced as a result of pedometer unreliability. By including a larger sample size, the nature of interactions between independent variables may have become more apparent, while making perceived associations with step and activity counts more representative of the wider population, as demonstrated by Chambers et al (2021).

A final limitation to the study includes the inconsistency of data available between sound and arthritic cohorts. While LOAD score (an indicator of OA severity) was recorded for arthritic individuals, this was not the case for their sound counterparts. Although the use of such a staging tool may seem irrelevant for clinically sound dogs, the availability of the associated data could aid the interpretation of results by ruling out or indicating the potential inclusion of undiagnosed OA within the sound cohort, while allowing for a larger sample size when exploring associations with osteoarthritis severity. Inconsistency in data availability was also observed in the arthritic cohort, whereby activity data were not collected during play, meaning the relationship between activity counts and activity type could not be explored for dogs with a confirmed diagnosis of OA.

To further explore the potential for accelerometers to be used in a diagnostic capacity, for detecting and monitoring gait impairing conditions in companion animals, the transferability of the step detection algorithm to other quadruped species should be investigated. As the population of domestic cats in the UK is second only to that of dogs (PDSA 2023), while the incidence rate of feline OA is similar to their canine counterparts, affecting approximately 82% of cats exceeding the age of 14, and 61% of cats exceeding the age of 6 (Bennett et al 2012), it would be reasonable to consider this species a good candidate for investigation. To assess the transferability of the step detection algorithm to cats, accelerometer data and supporting video footage will be captured, before applying the step detection algorithm and comparing the resultant step counts with those obtained manually.

4.5 Conclusion

Accelerometers offer an opportunity to measure gait and activity parameters in companion dogs, whereby the longitudinal observation of some parameters may assist in the identification and monitoring of gait impairing conditions. This chapter highlighted the potential applications of two measurable parameters, activity counts, and the filtered step count.

The diagnosis of osteoarthritis may be best supported by the measurement of activity counts, as this parameter offers clear differentiation between sound and arthritic individuals, while demonstrating no change in response to arthritis severity. Such observations may however be due to the limited number of individuals recorded throughout this chapter, perhaps causing possible trends with osteoarthritis severity to be overlooked. Once diagnosed, measurement of the filtered step count may support the long term monitoring of osteoarthritis, as this parmeter changed with age, and arthritis severity. Despite this, more extensive validation would be required, to ensure steps were recorded reliably, and algorithms monitoring step counts in non-controlled environments excluded high energy play activities. Such validation would require the collection of baseline values for each parameter from a large cohort of individuals, representing a range of breeds, ages, and conformations.

Chapter 5. Estimating the Step Counts of Domestic Cats, Using a Validated Canine Pedometer Algorithm

5.1 Introduction

Cats are among the most popular companion animal species in the UK, second only to their canine counterparts, with approximately 11 million individuals owned by 24% of the British adult population (PDSA 2023). Although cat ownership may not be associated with the increase in exercise and time spent outdoors, observed by dog owners (Westgarth et al 2017), caring for a cat is linked to a range of health and welfare benefits, including reduced blood pressure and companionship (Nagasawa et al 2020), factors which may be influential in the popularity of the species. Additional aspects which may contribute to the observed popularity of cats as a companion animal is the projected longevity of the species, averaging at approximately 15 years, with the potential to exceed 20+ years (O'Neill et al 2014). Although the average life expectancy of domestic cats exceeds that of dogs, this is subject to a host of contributing factors, including breed, weight, outdoor access, and disease (O'Neill et al 2014).

Of the cats presented to primary-care veterinary facilities in the UK, the most frequently observed conditions include kidney and dental disease, hyperthyroidism, parasitic infestation, obesity, and degenerative joint conditions (O'Neill et al 2014). Of the diagnosed degenerative joint diseases (DJD), osteoarthritis is among the most common in cats (Lascelles 2010), with the prevalence of such conditions estimated to reach approximately 61-99% of the population, whereby incidence is strongly correlated with the age of the individual (Maniaki et al 2023).

As with the canine equivalent, feline DJD's are among the most common sources of chronic pain in cats (Maniaki et al 2023), with a range of symptoms including restricted mobility and activity, as well as altered grooming and changes in temperament (Stadig et al 2019). Despite the prevalence of DJD's, and their associated impacts on the health and welfare of the affected individual, such conditions often remain undiagnosed until later stages, perhaps due to the gradual onset of subtle symptoms (Lemetayer et al 2014).

When considering potential solutions to the problem of delayed diagnosis, human medicine demonstrates the validated diagnostic potential of sensor technology, whereby devices such as accelerometers have been used to identify and measure subtle changes in gait parameters for the detection of conditions such as Parkinson's disease and multiple sclerosis (Schlachetzki et al 2017; Severini et al 2017).

Previous use of accelerometers in feline studies have demonstrated the capacity for the automated detection of body postures and behaviours including eating, drinking and several gaits. Despite this, limitations are noted to arise when attempting to distinguish walking from behaviours including jumping and grooming (Andrews et al 2015; Smit et al 2023; Watanabe et al 2005). When considering the use of accelerometers in future studies, Garcia and Chebly (2024) suggest that research should focus on gait behaviours due to the difficulty associated with their classification as well as their potential for indicating health and welfare.

The potential use of accelerometers for monitoring feline health conditions was previously acknowledged by Lascelles et al (2007), whereby the measurement of activity counts was shown to support owner reported assessments of pain, while consideration of distance travelled highlighted improvements in mobility following interventions for osteoarthritis (Lascelles et al 2008). Before similar approaches could be applied to the detection of gait imparing conditions in cats, methods for the automated monitoring of gait parameters would first require development and subsequent validation.

While the development of automated methods can be time consuming, it is possible to adapt and transfer existing processes between species, as part of the One Health approach (Rock et al 2009). Previous chapters have defined a validated pedometer algorithm with the ability to estimate canine steps to a high degree of reliability, and while the same algorithm may be transferrable to use with cats, such applications would require extensive validation.

This short study aimed to explore the potential for transferring a validated canine pedometer algorithm to use with domestic cats. To do this, activity data and supporting video footage was recorded from seven clinically sound cats using an accelerometer and a series of GoPro cameras. Previous comparisons of canine and feline gait highlighted notable differences in hindlimb propulsion forces, whereby higher peaks were observed in cats, whose posture was considered to be more crouched throughout the stance phase of the step cycle when compared to their canine counterparts (Corbee et al 2014). To account for such differences in gait, front and hindlimb steps were manually identified and counted from the recorded video footage, before extracting corresponding sections of accelerometer data and applying the defined pedometer algorithm (Chapter 1). The reliability of the resulting pedometer generated step count was then explored using R^2, before assessing the interchangeability of manual and automated step counts using Bland-Altman plots.

5.2 Materials and Methods

5.2.1 Ethical Statement

All methods reported throughout this chapter were conducted following approval from Newcastle university's ethical review board AWERB Project ID No: ID 995.

5.2.2 Recruitment

A cohort of seven cats were recruited for participation in the study (Table 5.1).

Table 5.1 The sex and age of cats recruited for participation in the study, as well as the duration of data recorded from each individual.

Cat ID	Sex	Age (years)	Duration of data recorded (hours)
Cat 1	Male	9	5
Cat 2	Male	0.33	5
Cat 3	Female	0.29	4
Cat 4	Male	0.58	5
Cat 5	Male	2	1
Cat 6	Female	0.25	2
Cat 7	Female	0.25	2

Both male and female cats were recruited, with no upper or lower limit imposed on age. Despite this, exclusion criteria omitted participation from any individual with a pre-existing medical condition, as well as those with no experience of wearing a collar.

All participating cats were owned by the friends or family of the researcher, as well as by the researcher themselves, meaning that recruitment took place by simply sharing details of the protocol with known contacts.

5.2.3 Data collection

Following recruitment, data collection for each cat took place in the cat's own home, or a home known to the individual. At each location, cats were restricted to just one room, in which all data were recorded. Although the housing of cats in a consistent animal facility was briefly trialled, the acclimatisation period required for cats sampled in this location was not feasible. The first stage of the protocol involved allowing cats to acclimatise to the presence of the researcher. For individuals sampled in the home of the researcher, acclimatisation first involved taking the cat to the designated room within their carrier, before placing the carrier in a corner, facing outward, before opening the door and moving away, allowing the individual to emerge from the carrier at their own pace. Upon exiting their carrier, individuals were considered acclimated when they actively approached and initiated contact with the researcher, with no crouching in their gait or posture. For individuals sampled in their own home, researchers entered the designated room and sat on the floor, allowing cats to approach at their own pace. Cats were once more considered to be acclimated when they actively approached and initiated contact with the researcher, with no crouching in their gait or posture.

Once acclimated, two GoPro Hero 9 cameras were used alongside an Axivity AX6 accelerometer to record the activity of participating cats. The accelerometer was first attached to a lightweight nylon collar, using a self-adhesive vet wrap bandage, before synchronising the device with the GoPro cameras. To do this, the researcher held the accelerometer in their hand, before clapping their hands five times around the device, within view of the video camera. The collar was then fastened around the neck of the cats, adjusting the width to leave a two finger gap, and cameras were placed in their required positions, whereby one was located at on a high vantage point in the corner of the room, enabling a full view of the room, while the other was held in the hand of the researcher, enabling a close-up view of the cat. Cats were then recorded in intervals of 10-20 minutes throughout which, cats were first encouraged to approach the researcher using food based reward, whereby the food offered to each cat was selected by the owner, based on the preference of each individual. A range of toys were then used to encourage locomotion around the room. To do this, two categories of toys were used (figure 5.1), the first of which were independent toys, including small balls, as well as plush mice and birds, while the second category included interactive toys, whereby a plush animal or length of ribbon was connected to a handheld wand. Independent toys were first placed on the floor in front of the cat, before being pulled away from the individual in an ‘S’ shape. This process was repeated until the cat followed the movement of the toy with their eyes, upon which the researcher would throw the toy across the room, with the expectation that the cat would chase behind. The use of interactive toys first required the researcher to hold the wand in their hand, before making circular motions with their wrist, causing the toy or ribbon to move in a swirling motion on the floor. Once the cat approached the toy, the researcher then moved across the room, trailing the toy behind them, with the expectation that the cat would follow behind. To avoid the introduction of unfamiliar scents, cats were only offered their own toys. While this meant that the same range of toys were not used consistently between all cats, the availability of each toy category was consistent for all individuals.

Figure 5.1. Examples of toys used throughout the study. The top row includes toys in the independent category, while the bottom row includes toys in the interactive category.

At the end of each recorded duration, the collar was removed from the cat, and data were transferred from the accelerometer and video cameras to a hard drive. The process was then repeated until the required recording duration had elapsed (Table 5.1).

5.2.4 Data processing

While the entire duration of data recorded from all cats was used as part of a wider study, this study made use of the first 30 minutes of data recorded from each cat only. To do this, GoPro video chapters were first stitched together to form one continuous video clip for each recording duration, using ReelSteady Joiner v.1.3.2, before using VLC media player Version 3.0.20 to re-encode each video file to remove audio content. To ensure accelerometer data were sampled evenly at a rate of 100Hz, raw accelerometer data files were resampled using the omconvert conversion program within the OMGUI software. RStudio Version 4.3.0 was then used to read the resampled accelerometer data, before converting the date and time stamp to a numeric format, beginning at zero and increasing in increments of 0.01 between subsequent sample points. Column headers were then removed to ensure readability in the ELAN software.

For each of the sampled cats, resampled accelerometer data and video footage was imported to ELAN (Version 6.7), before synchronising the two data sources. This was done by identifying the video frame in which the first in the series of five claps commenced, before pairing this with the corresponding peak in the Z axis of the accelerometer data. Labels were then used to identify bouts of walking, in which all four limbs were visible, whereby walking was defined as 'forward locomotion achieved by taking a series of steps at a slow pace, with one step involving the cat lifting their paw from the floor and swinging the limb, before replacing paw on the floor' (Stanton et al 2015). For each bout of walking, start and end times were recorded, and the number of steps taken by the front and hind limbs were manually counted. This process was repeated until a total of 30 minutes of data had been labelled per cat.

Resampled accelerometer data were then imported to RStudio, and bouts of walking were extracted based upon the recorded start and end times. Individual walking bouts were then stitched together, in chronological order, creating a single data frame for each cat. Next, the degree of reliability to which the pedometer algorithm (Chapter 1) could predict feline steps was assessed. To do this, the algorithm was applied to the stitched data frames, previously created for each cat, before noting the generated output.

5.2.5 Statistical analysis

Manually counted steps were recorded in three categories, including the total step count, recorded from all four limbs across the entire 30-minute recording duration, as well as a front and hind limb step count, manually counted during the entire 30-minute recording duration from the front or hind limbs respectively. Manual recording of steps from the front and hind limbs would help to inform whether the pedometer algorithm had the potential to differentiate between front and hindlimb movements of cats, as this was not the case for dogs. Conversely, pedometer generated steps were recorded in one category, the pedometer step count. While it was possible to produce an additional category by filtering against irregular steps and shuffles, the expected frequency of cat steps differs to those of dogs, meaning it was unlikely that the filtered step count would perform reliably in this instance, as such, only the initial step count was recorded.

Descriptive statistics were first used to explore the central tendency and dispersion of manual and pedometer counted steps, before using R^2 to investigate the relationship between the pedometer generated step counts, and the three manual step count categories. Next, Bland-Altman statistics were used to calculate and plot the means and differences between values recorded for each step count category, indicating the level of agreement between the pedometer generated step count and the three manual step count categories.

5.3 Results

5.3.1 Descriptive Statistics

The pedometer algorithm predicted step count with a varying degree of reliability across all cats (Table 5.2). While the pedometer step count was most reliable for Cat_1, with a disparity of three steps when compared with the manually obtained total step count, the greatest difference was observed for Cat_7, whereby a disparity of 216 steps was noted between the total and pedometer step counts.

The manually obtained total step count demonstrated the greatest degree of variation between cats, followed by the pedometer generated counts (Mean = 468.86, 396.71, SD = 277.39, 224.51 respectively) (Figure 5.2). The least variation was observed in the hind limb step count, which was consistently lower than the counts manually obtained from the front limbs (mean = 218.71, 128.50, SD = 130.61, 149.33 respectively).

Table 5.2. Summary of manually obtained and pedometer generated step counts, as well as the duration of usable footage from which steps were counted for each individual. Footage was considered usable when cats were walking with all four limbs within view of the camera.

Cat ID	Cat Age	Total step count	Front limb step count	Hind limb step count	Pedometer step count	Usable footage (minutes)
Cat_1	9	751	404	347	748	4.4
Cat_2	0.3	481	249	231	395	2.5
Cat_3	0.29	141	76	65	218	1.3
Cat_4	0.58	98	54	44	178	1.2
Cat_5	2	420	221	199	226	1.9
Cat_6	0.25	823	444	379	658	3.7
Cat_7	0.25	570	304	266	354	2.1

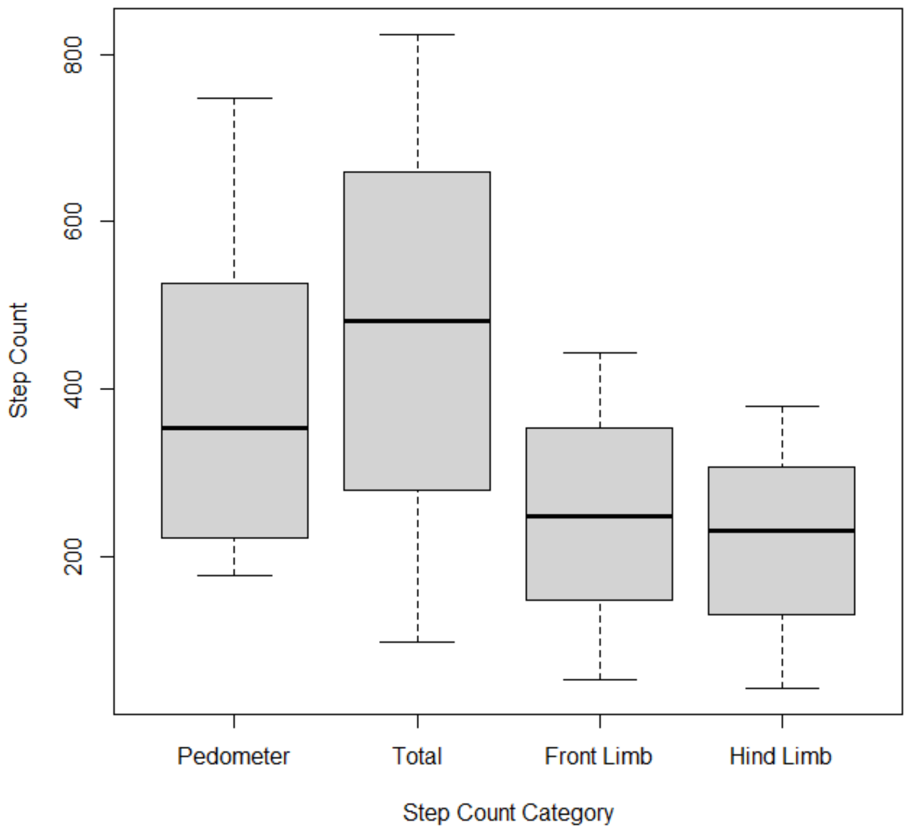


Figure 5.2. The degree of variation in the manually obtained and pedometer generated step count categories.

5.3.2 R^2

When compared to the manually obtained total step count, the pedometer algorithm consistently underestimated steps across all cats, while overestimating the step count recorded from the front and hind limbs respectively. Of the three manually obtained step counts, the pedometer algorithm most reliably predicted the front limb steps, with this count explaining approximately 81% of the variability observed in the pedometer generated step count (R^2 = 0.813). The reliability of the pedometer algorithm reduced slightly when considering the total step count (R^2 = 0.802) and was least reliable when considering the hind limb step count, with this category explaining approximately 79% of the variation observed in the pedometer estimated steps (R^2 = 0.791).

5.3.3 Bland-Altman Statistics

Further comparison of the manual step count categories with the pedometer generated counts highlighted mean differences ranging from 72.14 steps to -178 steps (Table 5.3), whereby the differences in step count for all individuals were observed between the 95% upper and lower limits of agreement (Figure 5.3).

Table 5.3. Limits of agreement and associated 95% confidence intervals for the differences observed between the pedometer generated step counts, and the manually counted categories. Upper and lower limits indicate the limits of agreement, within which 95% of differences should be placed if the pedometer algorithm is to be used interchangeably with the three manual step count categories. The mean differences between the manually derived step counts and the pedometer generated step counts (whereby pedometer counts were subtracted from manual counts), as well as the limits of agreement are displayed in figure 5.3.

Category	Mean Difference	Lower Limit	Lower 95% CI	Upper Limit	Upper 95% CI
Total step count	72.14	-174.24	35.05 to -383.53	318.53	527.82 to 109.23
Front limb step count	-146.43	-363.25	-179.07 to -547.43	70.391	254.57 to -113.79
Hind limb step count	-178	-422.79	-214.85 to -630.73	66.79	274.73 to -141.15

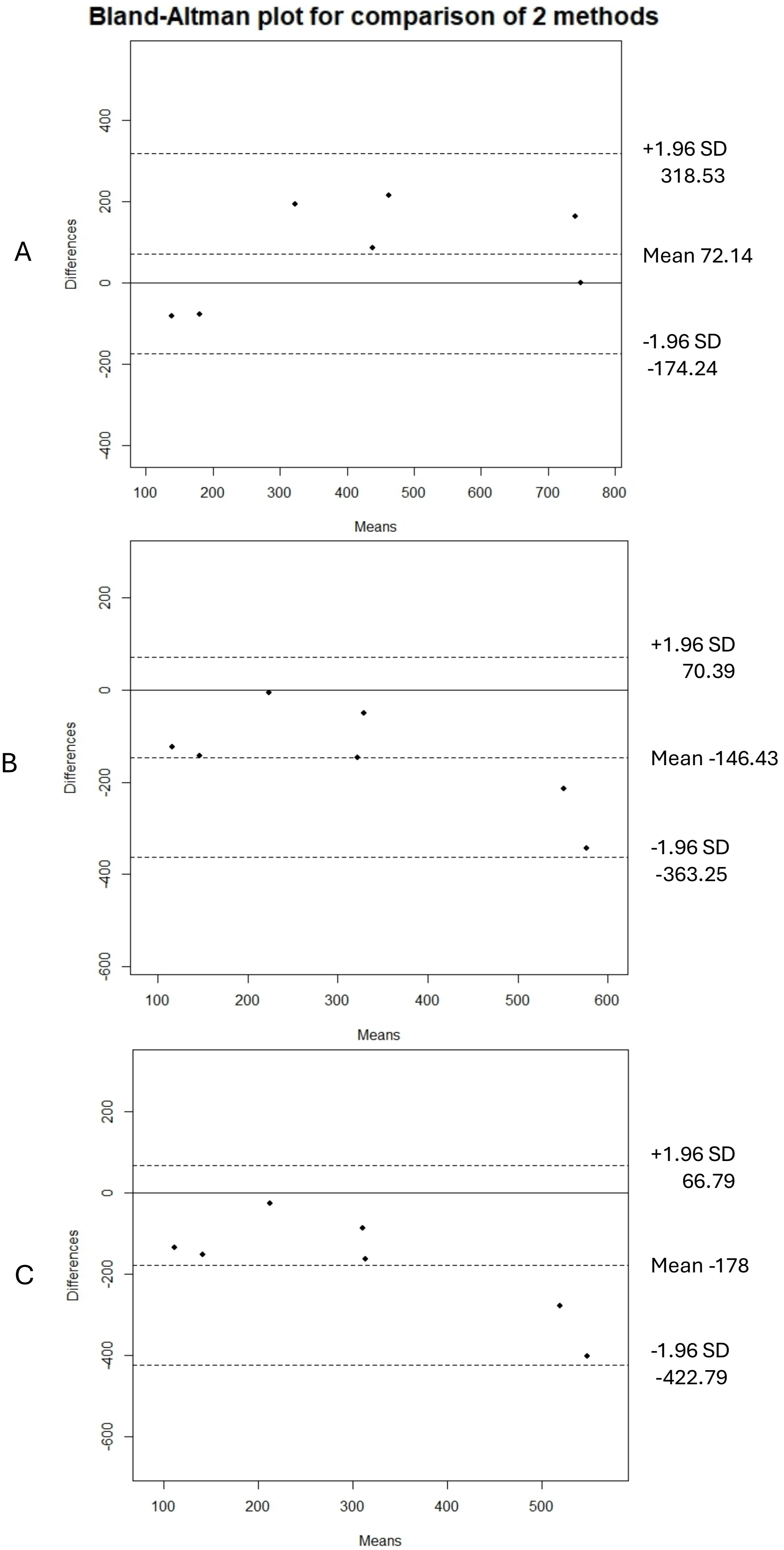


Figure 5.3. Differences between pedometer generated step counts, and manually obtained step counts (n=7). Upper limits of agreement are represented by the uppermost dotted lines, while lower limits of agreement are defined by the lowermost dotted lines. Central dotted lines represent the mean difference, or 'bias', which was calculated across all cats, with dots representing individual cats. Upper and lower boundaries define upper and lower 95% confidence intervals. Plot A highlights differences between the total step count and the pedometer step count, while plots B and C display differences between the Front limb step count and the pedometer count, as well as between the hind limb step count and pedometer count respectively.

5.4 Discussion

To assess the potential scope for applying a validated canine pedometer algorithm to use with domestic felines, we collected activity data and video footage from seven clinically sound cats, using an accelerometer and a series of two GoPro cameras. Once cats were recorded, the start and end points of individual bouts of walking were identified in the video footage, before counting and recording the associated step counts in three categories: the front limb step count, the hind limb step count, and the total count from the front and hind limbs. Sections of accelerometer data corresponding to bouts of walking were then extracted, based upon the recorded start and end points, before being stitched together to form one single data frame, to which the pedometer algorithm, defined in Chapter 1, was applied. The pedometer generated step count was then recorded and compared to the three manually obtained step counts.

A large degree of variation was identified in the number of steps manually recorded for each individual, within all three step count categories, with the largest proportion of variation demonstrated by the total step count. Although the total step count consisted of steps observed from the front and hind limbs, the contributing counts were uneven, with front limb steps exceeding those from the hind limbs for all sampled cats.

The step count category most reliably predicted by the pedometer algorithm varied between cats, however, when considering the entire cohort, the reliability of the front limb step count marginally exceeded that of the total and hind limb counts. The indication that all manually obtained step counts offered a similar degree of reliability was supported by the Bland-Altman correlation analysis, whereby all differences between the pedometer count and each manual count fell within the 95% limits of agreement, suggesting that each step count could be used interchangeably.

When considering potential sources of variation in the number of steps manually counted from each individual, demographic factors such as age should be considered. Older cats sleep for a larger proportion of the day, and are less inclined to play when compared to kittens (Sordo et al 2020). As a large proportion of the sampled cohort were kittens, below the age of one, it is possible that these individuals participated in more play than their adult counterparts, potentially causing their gait to fall beyond the definition of walking used in this study, subsequently leading to the exclusion of such steps from the manual step counts, perhaps limiting the resulting count once more.

Additional factors contributing to the variation in manually counted steps could include the individual's level of interest in the type of food and style of play made available. Although food and play were used to encourage walking, cats often have preferences for particular styles of play and engagement with humans (Delgado and Hecht 2019), while food may be considered on a scale of associated value, depending on factors such as texture, smell and flavour (Bradshaw et al 1996). With that in mind, it is possible that the step count observed from each cat may have been restricted, or enhanced, by their level of interest in the food and play offered by the researcher.

The number of observed steps may have been further influenced by the presence of the researcher in the cat's home, or, alternatively, by cats' own presence in the home of the researcher. As cats are sensitive to changes in their environment, whereby deviations from normal routine can lead to modified behaviour (Amat et al 2016), it becomes reasonable to consider that cats may suppress behaviours such as walking, in response to environmental change, perhaps restricting the number of steps observed.

While the front limb step counts appear to outweigh those of the hindlimbs, steps were counted from durations of footage in which all four limbs were visible, with counts ending when any limb strayed from view, perhaps restricting the number of steps which could be counted from the hind limbs. As such, the disparity between front and hind limb step counts may not be representative of typical feline gait.

When applied to canine activity data, the pedometer algorithm predicts steps from the thoracic forelimbs with a high degree of reliability, however, when considering the oldest cat sampled in this study (Cat_1), the algorithm most reliably predicted the total step count, from all four limbs, with a difference of just three steps when compared to the manual count. The algorithm's ability to predict step count from all four limbs to such a high level of reliability, suggests there may be differences in the way in which dogs and cats walk, making hindlimb steps as detectable as those taken by the forelimbs. Despite this, reliability of the pedometer step count reduced when compared to the total step count of subsequent cats, suggesting that the precision observed for Cat_1 may in fact be due to individual variation in gait. Conversely, the pedometer algorithm most reliably predicted the front limb step count of Cat_5 and Cat_7, with a disparity of just five and 50 steps respectively when compared to the manually obtained count. As the two individuals were younger than Cat_1, it is possible that the perceived reliability of differing step counts may be caused by age related variations in gait, whereby similarities with canine gait reduce with increasing age. Despite this, such considerations are entirely speculative, as the sampled cohort included just two adult cats, of which, one was a mature adult, and one was a young adult, while the remaining cats were kittens, at less than one year old. To better understand the gait of cats, and indeed whether this changes with age, an additional study would be required, whereby repeat sampling would aim to capture individual variation in gait, from a large sample size, encompassing a broad range of ages.

To better understand the reliability of the pedometer step count when compared to the three manually obtained counts, Bland-Altman plots were used. Although the differences between the manual and pedometer step count categories fell within the upper and lower 95% limits of agreement, suggesting that each step count could be used interchangeably, it is likely that this result was influenced by the large confidence intervals, arising due to the small sample size and large degree of individual variation. To improve certainty in the results, smaller confidence intervals would be required, a factor which could be achieved by conducting repeat sampling of a larger cohort of cats.

Despite the perceived interchangeability of each step count category, the R squared coefficient of determination suggested that the front limb step count was the most reliable of the three manual counts, followed by the total step count and the hind limb step count. The front limb step count accounted for 81% of the variability observed in the pedometer count, meaning that a small degree of unreliability remained.

It is possible that the remaining unreliability was due to fundamental differences in canine and feline gait, whereby cats adopt a more crouched posture and exert greater hindlimb propulsion forces than their canine counterparts (Corbee et al 2014). Meanwhile, further potential sources of unreliability include human error when manually counting steps, as well as errors which may arise from combining individual sections of accelerometer data. As steps were counted from durations of footage in which all four limbs were visible, it was necessary to extract the corresponding sections from the accelerometer data, to ensure the pedometer algorithm was applied only to data from which step count could be confirmed from supporting video footage. As the pedometer algorithm worked in a sliding window of 20 seconds (Ladha et al 2018), it was then necessary to combine all bouts of walking, to ensure that data were of a sufficient length to generate a step count representative of all instances of walking. Despite this, the pedometer algorithm detects steps based upon events occurring before and after the identified step candidate, meaning that steps may be artificially generated, or wrongly excluded, as a result of combining data. When regarding the potential error associated with the use of combined accelerometer data, the pedometer's requirement for data with a minimum duration of at least 20 seconds becomes a limiting factor to this study, particularly when considering the sedentary nature of cats (Slingerland et al 2009).

Additional limitations of the study include the small sample size, and disproportionate age representation. As data were collected on just one occasion, from a limited cohort of seven clinically sound cats, of which only two individuals exceeded the age of one, it was not possible to ascertain sources of unreliability for the pedometer step count, while these could include factors such as age, human and processing error, as well as individual variation.

The study was further limited by the varied locations in which cats were sampled. Although only those individuals with previous experience of the researcher and their home were sampled in this location, cats can often modify their behaviour in response to subtle changes in environment and routine (Amat et al 2016), perhaps influencing the observed step count and perceived reliability of the pedometer algorithm among the visiting individuals.

The use of multiple sampling locations also limited the extent to which steps could be counted from certain individuals. Although the positioning of the two GoPro cameras was similar at each location, whereby one camera was handheld, with the remaining camera placed in a high vantage point, with a view of the entire room, the visibility of each cat depended on factors such as lighting and furniture placement. Although the counting of steps and subsequent matching of video and accelerometer data took place only for sections of footage in which the cat was walking, and all four limbs were within view, differences in environment may have altered the degree of reliability to which steps were counted for each individual.

The study was also limited by the nature of the pedometer algorithm. Although there is an indication that the pedometer can detect steps from the front and hind limbs of cats, the algorithm was developed to detect canine steps from the front limbs only (Ladha et al 2018), meaning that discrete counts cannot be produced for the front and hind limbs when applied to feline data. As such, it is not possible to definitively establish which set of limbs is responsible for the reliability or unreliability of the pedometer generated step count. Despite this, the strongest correlation is observed between the forelimb and pedometer estimated counts, suggesting that the hindlimbs may be the source of observed unreliabilities.

Additional limitations include the fact that the pedometer algorithm has the ability to produce a filtered step count, in which irregular steps such as shuffles are removed from the final step count. As this stage of the algorithm was developed solely for dogs, based upon their height and expected step frequency, it was not possible to apply to cats, meaning that irregular steps such as shuffles were not identified or removed from the pedometer step count. While the inclusion of such a filter could improve the reliability of the pedometer step count, the height of sampled individuals, as well as their expected step frequency would first be required.

This short study highlighted the variability in step count among individual cats, however, to better understand the sources of such variation, as well as the potential impacts of age, a longitudinal study would be required, involving the manual counting of steps from individuals in a large cohort, with a diverse range of ages, using repeat sampling. Furthermore, while the study demonstrated scope for applying the canine pedometer algorithm to feline activity data, further validation is required, a process which would once more involve a large cohort, with a diverse range of ages, breeds, and conformations, sampled in one single location.

Despite the need for further validation, this sudy highlighted the transferability of a pedometer algorithm between two companion animal species. When considering the degree of reliability to which steps were predicted for domestic cats, it becomes reasonable to consider potential scope for use in other quadruped species, including livestock and wild animals. Although such applications would once more require extensive validation, transfer of the algorithm could assist in the monitoring of herd health and welfare, while perhaps adding additional context to remote sensing data.

5.5 Conclusion

Sensor based technology can be used to monitor the activity of companion animals, whereby the measurement of activity parameters may allow inferences to be made regarding the health and, or welfare of individuals. While such inferences may be of interest to the owners of companion animals, these may be particularly beneficial to those caring for an individual with a chronic health condition, for which medication and monitoring is required. Before sensor technology could be deployed for such a purpose, their capability for reliably detecting and measuring activity-based parameters must be evaluated and validated.

This study investigated the potential for applying a validated canine pedometer algorithm to the activity data of domestic cats, to produce a reliable estimation of step count. While the perceived reliability of the pedometer step count suggests there is potential scope for transferring the use of the algorithm between species, a better understanding of individual variation in feline gait would be required before sources of error observed in the estimated count could be identified. Such understanding could be achieved by longitudinally cataloguing the gait of a large cohort of cats, encompassing a range of breeds, ages and conformations.

While there remains much to explore with the use of accelerometers, this short study suggests that there may be scope for transferring automated methods of step detection between companion quadruped species.

Chapter 6. General Discussion

Canine osteoarthritis (OA) is the most commonly diagnosed degenerative joint disease among dogs (Lascelles et al 2002). Affecting approximately 80% of individuals exceeding the age of eight, and 20% of those exceeding the age of one (Anderson et al 2018; Fritsch et al 2010), OA results in the degeneration of cartilage in synovial joints, reducing the function of the joint, while causing chronic pain (Bland 2015). Although OA is considered to be a major health and welfare concern, the condition often remains undiagnosed until routine and unrelated veterinary appointments, delaying the provision of pain relief and interventional treatment (Cachon et al 2018). When considering potential solutions to the problem of delayed diagnosis, human medicine demonstrated the diagnostic capabilities of sensor technology, such as accelerometers, for detecting and monitoring the progression of gait impairing conditions such as Parkinson's disease and multiple sclerosis (Schlachetzki et al 2017; Severini et al 2017). This thesis aimed to explore the potential use of accelerometers in veterinary therapeutics for the diagnosis and monitoring of OA, implementing a one health approach.

To meet the aim of the thesis, three objectives were outlined: 1) to establish the potential impact of OA on step count and activity counts; 2) to gather expert opinion on the role of sensor technology in veterinary therapeutics and specifically, for the detection and monitoring of OA; and 3) to validate a published pedometer algorithm for use with arthritic dogs. The consideration of expert opinion then led to the expansion of the thesis, and the introduction of a fourth objective, whereby the transferability of the defined pedometer algorithm between companion quadruped species was explored.

This chapter details the level of success to which each of the objectives were achieved, before discussing the extent to which the overall aim of the thesis was met.

6.1 Objective 1: The relationship between canine osteoarthritis, step count and activity counts.

The six-minute walk test (6MWT) is a performance-based test, which can be used in human medicine to assess the physical function of patients with knee osteoarthritis, and to provide outcome measures for individuals after undergoing knee replacement surgery (King et al 2020). The same test has also been applied to studies involving domestic dogs, whereby the effects of pulmonary and neuromuscular diseases on an individual's exercise tolerance were investigated (Swimmer et al 2011; Cerda-Gonzalez et al 2016). In each of these studies, both human and canine, the distance travelled by each individual was recorded as the outcome measure. Accelerometers have previously been used to infer the distance travelled by a dog, based on the number of steps taken by the individual, leading to the development and publication of an open-source pedometer algorithm (Ladha et al 2018). Despite this, the results published in Chapter 2 appear to be the first resulting from the retrospective application of a 6MWT to an archived accelerometer dataset, in which the recorded outcome measures were step count and activity counts, as opposed to distance travelled. While it was found that the number of steps taken throughout the six-minutes of highest continuous activity per day was not associated with the diagnosis of OA, the mean activity count, observed at the same time, was associated with age and OA. Such observations suggest that while dogs may not alter the number of steps taken in response to the disease, a result which may be due to factors such as effective management of the condition, as well as the intermittent nature of associated symptoms (Bland 2015; Belshaw 2017), the amount of energy expended while walking decreases in affected individuals. Such results are supported by De Ortiz et al (2022).

6.2 Objective 2: The Use of Technology in Veterinary Therapeutics and For the Long-term Monitoring of Canine Osteoarthritis – A Delphi Consultation Study

The Delphi Consultation framework (Nasa et al 2021) was used to collect the opinion of pet owners and veterinary professionals regarding the potential role of sensor technology in veterinary therapeutics, to address the unmet needs of vets and owners, as well as for the early detection and monitoring of OA. The topic of interest was first split into two key themes; 1) the use of sensor technology in veterinary therapeutics; and 2) the use of sensor technology for the early detection and monitoring of OA, before a discussion board was used to inform the development of series of questionnaires. While the initial stage of the process typically involves an in person scoping meeting Rioja-Lang et al (2020) demonstrated the explored use of discussion boards as an alternative approach, which were implemented in Chapter 3 in response to lockdown and social distancing measures enforced due to the Coronavirus pandemic. Although the use of a discussion board was necessary due to the set of novel circumstances under which chapter 3 was completed, a low level of stakeholder engagement was observed, suggesting that in-person scoping methods may still be preferable.

The questionnaire highlighted stakeholder specific difficulties faced in the vet-owner relationship, before suggesting ways in which such problems could be overcome with the use of sensor technology. An interest in the specified technology was highlighted, and a majority of participants from each stakeholder group demonstrated a willingness to use technology, subject to a host of conditions, whereby concerns surrounding the use of the described technology included cost, ease of use, and the time taken to use such a device, as well as the accuracy of the data collected.

Final questions were aimed solely at veterinary professionals and were focussed upon the detection of OA. Responses highlighted the current methods for diagnosing OA in general practice, before highlighting gait parameters measurable with the use of sensor technology, alongside the perceived usefulness and practicality associated with the measurement of each parameter. From this, it was possible to identify priority gait parameters for measurement for the detection of OA with the use of accelerometers, including step length, stride count, and step count.

6.3 Objective 3: Cataloguing the Gait of Sound and Arthritic Dogs.

Chapter 2 applied a published pedometer algorithm to the archived activity data of sound and arthritic dogs, allowing for the implementation of a natural version of a 6MWT. Despite this, the defined algorithm was never validated for use with arthritic individuals, while a lack of supporting video footage limited the extent to which perceived interactions between OA and step count could be interpreted. By applying the pedometer algorithm to the activity data of arthritic individuals, with supporting video footage, Chapter 4 sought to validate the pedometer algorithm for use with individuals diagnosed with OA.

The results presented in Chapter 4 initially supported those presented in Chapter 2, whereby the mean activity counts of sound dogs once more exceeded those of arthritic individuals, indicating a greater degree of energy expenditure when walking. Chapter 2 then highlighted a further relationship between mean activity counts and OA severity, however this was not supported by Chapter 4, whereby OA severity appeared to have no effect on the level of energy expended.

Chatper 2 and 4 indicated no effect of OA or age on the initial step count. Despite this, exploratory regression models completed in Chapter 4 highlighted the effect of age on the filtered step count of arthritic individuals, before suggesting a level of correlation between age and LOAD score, when used as an indicator of OA severity.

Additionally, Chapter 4 highlighted activity dependent variation in the mean activity counts of sound dogs, offering a unique view of the effect of activity type (in this case play and walking), on the intensity of energy expended by sound dogs. Meanwhile, the individual variation in activity counts among arthritic individuals highlighted potential pitfalls associated with applying activity thresholds developed for clinically sound dogs Yam et al (2011) to those with gait impairing conditions, indicating scope for the development of more appropriate thresholds for affected individuals.

6.4 Objective 4: Estimating the Step Counts of Domestic Cats, Using a Validated Canine Pedometer Algorithm

The pedometer algorithm developed by Ladha et al (2018), defined in Chapter 2, was applied to the activity data of domestic cats, responding to interest expressed in Chapter 2, while addressing the lack of literature on the topic. The activity data presented in Chapter 4 highlighted a large extent of individual variation in feline gait, whereby application of the canine pedometer algorithm resulted in the estimation of steps within a reasonable degree of reliability when compared to the three manual step count categories (front limb step count, hind limb step count and the total step count). Despite this, the greatest degree of reliability was observed when comparing the pedometer step count with the manually obtained total step count. While Bland-Altman statistics indicated that pedometer generated step counts could be used as an alternative to manually counted steps, based on the means and differences calculated between the step counts, this result was likely due to the large degree of standard error resulting from the small sample size and the large degree of individual variation observed.

6.5 Implications

The diagnosis, treatment, and subsequent monitoring of conditions such as OA involves a multistage process described in Chapter 3 as the ‘pathway to effective diagnosis’. While the specified pathway first depends upon the owner’s ability to recognise symptoms and seek veterinary assistance, this stage can often be delayed for individuals with undiagnosed OA, as the associated symptoms can be subtle, intermittent, and overlooked by owners (Belshaw et al 2017; Matthews et al 2014). Such issues frequently result in the delayed diagnosis of OA during routine and unrelated veterinary appointments, which are often restricted to a duration of just 10 minutes (Robinson 2016). While an unexpected diagnosis can blindside owners, the short appointment times observed in general practice may limit communication and information exchange between vets and owners, factors which could strain the relationship between the two stakeholders. Despite the pitfalls associated with the pathway to effective diagnosis, the results presented in Chapter 3 demonstrate the ways in which sensor technology could be used to address the unmet needs of vets and owners, perhaps improving the relationship between the two stakeholders. The predicted benefits of sensor technology may be of particular importance when considering the increased workload faced by a number of veterinary professionals, following the recent rise in pet ownership (McMillan et al 2024). It is therefore perhaps promising to consider that a majority of participants belonging to each stakeholder demographic indicated a willingness to use such technology, subject to exhaustive validation.

When considering condition specific applications for novel technologies, the potential scope for accelerometers to differentiate between sound and arthritic individuals was demonstrated in Chapters 2 and 4, whereby a reduction in mean activity counts was associated with a diagnosis of OA. Although chapter 2 further highlighted associations between mean activity counts and the age of the individual, no such interactions were supported by Chapter 4. When considering the observed interactions between OA and mean activity counts, the ability to longitudinally measure this parameter with the use of accelerometers may offer a non-invasive method for supporting the detection and diagnosis of OA in dogs.

Exploratory analysis in Chapter 4 also detected correlations between age, LOAD score and the filtered step count generate by the pedometer algorithm, perhaps highlighting a parameter of interest for non-invasively monitoring the progression of OA and the effectiveness of treatment.

The use of accelerometers for monitoring the gait of other domestic quadruped species was explored in Chapter 5, whereby the pedometer algorithm was applied to the activity data of seven healthy cats. Although a large extent of individual variation was observed in the manually recorded step counts, the pedometer algorithm was able to predict steps to a reasonable degree of reliability, demonstrating scope for transferring methods for automated step detection between species. When considering the extent of individual variation observed in Chapter 5, application of the algorithm to other quadruped species would likely benefit from a longitudinal approach.

Such an approach would enable the creation of a baseline for each sampled individual, to which anomalous measurements could be compared, perhaps supporting the automated detection and monitoring of gait imparing conditions Figure 6.1). While the described approach would require extensive validation, the use of these have been previously recommended for dogs (Colpoys and DeCock 2021) and studied in cattle, whereby sensor data has been used to predict calving and detect disease (Gusterer et al 2020; Rutten et al 2017; Eckelkamp et al 2020).

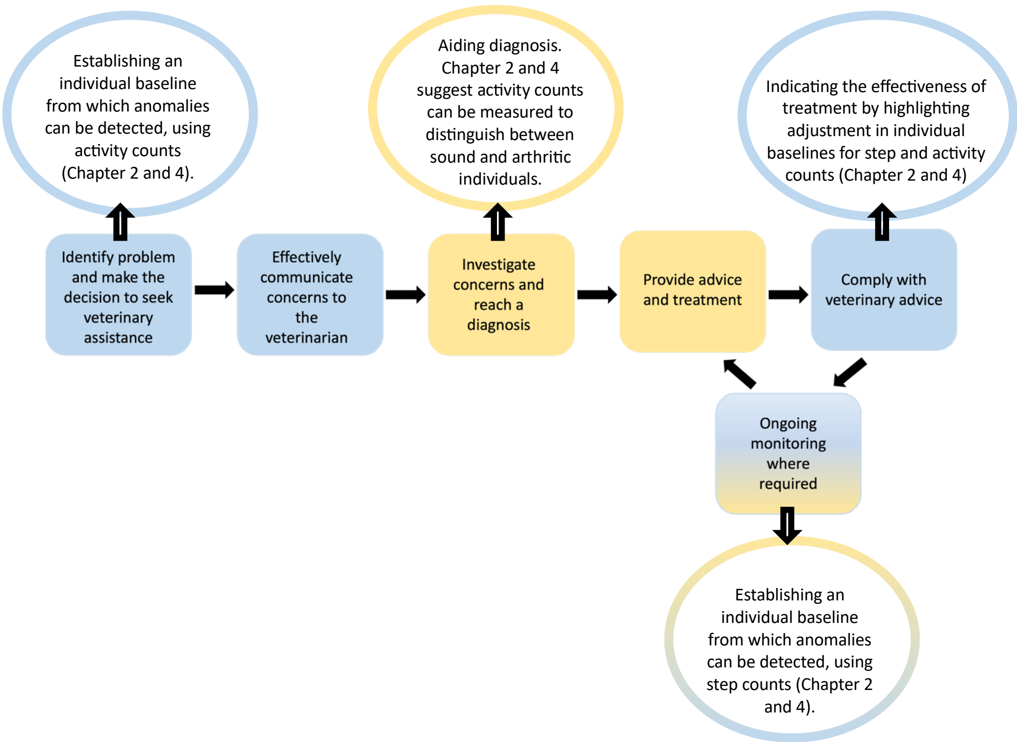


Figure 6.1. Ways in which the longitudinal monitoring of activity data could support the detection and management of gait impairing conditions.

While the longitudinal measurement of gait and activity parameters could have a range of applications, the required level of reliability may vary between potential uses. Although the measurement of gait and activity parameters would require a high level of reliability for research applications, a lower level of reliability may be acceptable for the day to day monitoring of low level fluctuations in companion animals. The required level of precision may also vary within potential uses, for instance disease detection, whereby the required level of reliability would depend on the measurable difference caused by the disease. If the measurable difference was large, then a lower reliability may be excusable, however for small differences in disease related changes to parameters, a greater degree of reliability would be required. A lower degree of reliability may also be acceptable for the longitudinal monitoring of wild animals, however this would be subject to the potential for accruing systemic error, a factor which requires deeper understanding from further investigation.

6.6 Limitations of the Studies

In addition to the described implications, the studies included in this thesis were associated with a range of limitations. While limitations were discussed consistently within each chapter, these are summarised and explained below.

The first limitation arose from the lack of video footage in support of the archived accelerometer data used throughout Chapter 2. While the study described in this chapter involved the identification of the six-minutes of highest continuous activity per dog, per day, from which step counts would be estimated, Chapter 4 highlighted significant associations between mean activity counts and activity type. As mean activity counts recorded during play were considerably higher than those obtained while walking, it is possible that a proportion of step counts reported in Chapter 2 were estimated from a recorded bout of play, as opposed to locomotion. As some play styles, such as tug-of-war, may result in a reduced step count when compared to walking, it is possible that step counts estimated during bouts of play may not be representative of the individual, perhaps impacting the perceived relationship between osteoarthritis and step count.

While Chapter 4 highlighted the potential applications of the filtered step count for monitoring the progression of OA and the effectiveness of associated treatment, the investigation of this parameter was entirely exploratory. Although the filtered step count of arthritic individuals was observed to increase with age and condition severity, this interaction was observed from a small sample of five individuals, meaning the obsereved effects may not be representative of all arthritic dogs.

A third limitation of the study includes the reduced reliability of the pedometer algorithm, observed in Chapter 4. While the manual step count explained approximately 99% of the variation observed in the initial step count estimated by the pedometer algorithm in Chapter 2, this reduced to approximately 80% in chapter 4. While the reduction in reliability may be due to a series of factors including the use of stitched data, as well as the level of drift observed between the video and accelerometer data sets, the impact of such unreliability on the perceived relationship between step count and OA is unclear.

The fourth limitation of the study arises from Chapter 3. While the implementation of the Delphi Consultation process enabled the collection of expert opinion regarding the possible use of sensor technology for the early detection and management of OA, time restrictions meant that it was not possible to explore each of the parameters predicted by veterinary professionals to have diagnostic potential. As such, the possible use of the suggested parameters in a diagnostic capacity remains unknown.

A final limitation of the study was observed in Chapter 4, whereby no refinements were implemented before applying the canine pedometer algorithm to the activity data of cats. Although the algorithm was able to predict the steps of domestic cats to a reasonable degree of reliability, this operated on a sliding window of 20 seconds, whereby step counts could not be estimated from data with a lesser duration. To ensure that activity data met the minimum required duration of 20 seconds, all data from which steps were manually counted was stitched together, perhaps increasing the scope for error. In addition to this, the filtered step count presented in Chapters 2 and 4 was estimated in relation to the expected step frequency of dogs, calculated using the height of the sampled individuals, however no height information was collected for participating cats, meaning a representative filtered step count could not be estimated.

6.7 Future Research

This thesis sought to explore the potential role of sensor technology in veterinary therapeutics, to address the unmet needs of vets and owners, and to enable to early detection and monitoring of canine osteoarthritis. Although a range of studies have been described throughout chapters 2-5, there remains much to explore with the use of accelerometers, examples of which are detailed below.

The reliability of step counts estimated by the pedometer algorithm reduced in Chapter 4, when compared to those estimated throughout Chapter 2. While potential sources of unreliability have been discussed elsewhere, such observations necessitate further validation of the algorithm before its use can be continued with both sound and arthritic dogs. Such validation should allow for individual variation in gait by sampling a large cohort of sound and arthritic dogs, including a range of breeds, ages, conformations, and stages of disease severity, using motion capture, a system which is often considered to be the gold standard method of gait analysis (Schlachetzki et al 2017).

The step and activity counts of sound and arthritic dogs were recorded and compared throughout Chapters 2 and 4, however no longitudinal study was completed. Despite this, repeated sampling of the same individual could allow for the comparison of activity data recorded before and after a diagnosis of OA, perhaps allowing for further isolation of disease related changes in measured gait parameters from those associated with age. Furthermore, the repeat sampling of arthritic individuals before and after the provision of interventional treatment may allow further conclusions to be drawn regarding the effects of condition management on the recorded gait parameters.

Additional areas for future research are linked to the application of the pedometer algorithm to the activity data of domestic cats. While Chapter 4 highlighted scope for transferring the algorithm between companion animal species, a moderate level of unreliability was observed in the estimated step counts. As such unreliability may arise from the large extent of individual variation detected in the manually counted steps, validation of the pedometer algorithm for continued use with cats would first require a better understanding of individual and age relation variation in feline gait. To achieve this, a longitudinal study would be required, encompassing a large cohort of individuals with a broad range of breeds, ages, and conformations. Upon completion of such a study, it is likely that the expected frequency of feline steps could be estimated, allowing for the refinement of the pedometer algorithm to produce a filtered step count.

6.8 Concluding Statement

The studies detailed throughout this thesis demonstrate the possible applications of sensor technology within veterinary therapeutics, to address the unmet needs of veterinary professionals and pet owners, while also identifying two gait parameters, for which automated measurement may assist the monitoring of canine osteoarthritis. Firstly, the collection of expert opinion highlighted potential pitfalls which can obstruct the pathway to effective diagnosis and treatment, before highlighting the ways in which novel technologies could be implemented to overcome these, perhaps signposting methods by which the relationship between vets and owners could be strengthened. Next, by recording mean activity counts, it was possible to distinguish between sound and arthritic dogs, suggesting that the measurement of this parameter may assist the automated detection and diagnosis of OA. Furthermore, correlations were observed between the filtered step count, age and LOAD score of arthritic dogs, suggesting that the measurement of this parameter may be of benefit to the automated monitoring of OA progression. As the effects of OA severity on the filtered step count could not be separated from those associated with age, it would not be feasible to measure this parameter in a diagnostic capacity, before carrying out further work to isolate the effects of each predictor variable. Finally, the application of the canine pedometer algorithm to the activity data of domestic cats highlighted the scope for transferring automated methods of step detection between companion quadruped species. Despite this, the continued application of the algorithm to feline data would first require refinement and extensive validation, to ensure the reliability of predicted steps. The sustained development of automated methods for detecting and measuring gait parameters may support the processes by which gait impairing conditions such as OA are diagnosed and monitored, while perhaps strengthening the relationship between veterinary professionals and pet owners.

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Appendix A. Participant Details

Table 1A. Details of control and osteoarthritic dogs included in the accelerometer dataset.

Dog ID	Type	Age	Sex	Neuter Status	LOAD Score
C047MDB	Control	2.58	M	Y	2
C040MDB	Control	11	M	Y	19
C044FLA	Control	7	F	Y	NA
C045FLA	Control	2	F	Y	NA
C048MDB	Control	13	M	Y	12
C049FDB	Control	9	F	Y	7
C050FDB	Control	3	F	Y	4
C051FDB	Control	13	F	Y	24
C052FDB	Control	3	F	Y	3
C053FDB	Control	5.25	F	Y	1
C054FDB	Control	13	F	Y	2
C055FDB	Control	8	F	Y	15
C056FDB	Control	9	F	Y	17
C043FJO	Control	11.92	F	Y	9
C042FJO	Control	9	F	Y	9
C039FDB	Control	13	F	Y	6
C041FLA	Control	8.75	F	Y	9
C036FDB	Control	2	F	N	1
C038MDB	Control	7.5	M	Y	3
C037MDB	Control	7.5	M	Y	5
C035MDB	Control	6	M	Y	9
C033FDB	Control	4	F	Y	3
C034FDB	Control	5	F	Y	6
C031FDB	Control	2.75	F	Y	4
C024MDB	Control	3.5	M	Y	3
C032FDB	Control	2.75	F	Y	5
C030FDB	Control	8	F	Y	3

C028MDB	Control	7	M	N	6
C026MDB	Control	2	M	Y	0
C023MDB	Control	4	M	Y	0
C025MDB	Control	7	M	Y	0
C022MDB	Control	2	M	Y	2
C021MDB	Control	1.5	M	Y	1
C016FGK	Control	2	F	NA	3
C029FDB	Control	3.5	F	Y	6
C002FGK	Control	6	F	Y	9
C017FGK	Control	5	F	Y	2
C018FGK	Control	1.9	F	NA	1
C003MGK	Control	6	M	NA	1
C006MGK	Control	2	M	N	0
C015FGK	Control	10	F	NA	2
C014FGK	Control	5	F	Y	3
C007FGK	Control	10	F	Y	10
OA026MDB	OA	13	M	Y	26
OA025MD	OA	10.58	M	Y	7
OA027MDB	OA	8	M	Y	15
OA028FDB	OA	9	F	Y	12
OA029MDB	OA	16	M	Y	20
OA024MDB	OA	8	M	Y	21
OA023MCL	OA	10	M	Y	26
OA019MCL	OA	15	M	Y	33
OA018FCL	OA	14	F	Y	14
OA015FCL	OA	12	F	Y	11
OA007MCL	OA	9	M	Y	2
OA020MZB	OA	13	M	Y	13
OA008FZB	OA	9	F	Y	23
OA002FZB	OA	11	F	Y	52
OA005FZB	OA	14	F	Y	25

OA010MZB	OA	8	M	Y	24
OA013FZB	OA	11	F	Y	16
OA016FZB	OA	9	F	Y	23
OA001MZB	OA	10	M	Y	14
OA003MZB	OA	14	M	Y	36
OA006FZB	OA	11	F	Y	26
OA009MZB	OA	11	M	Y	21
OA011MZB	OA	8	M	Y	15
OA012FZB	OA	10	F	Y	36
OA014FZB	OA	11	F	Y	20
OA017FZB	OA	13	F	Y	10
OA021MZB	OA	9	M	Y	16
OA022MZB	OA	9	M	Y	7
OA004MZB	OA	13	M	Y	22

Appendix B. Description of a Novel Device Included in the Discussion Board

The device, Sensum:Pet, will integrate a new multi-function injectable biosensor and ID chip, with a wearable ambient sensor, from which combined data will be presented through a user friendly interface. It is intended that Sensum:Pet will inform early condition identification, while supporting rapid intervention and telehealth communications.

The chip component of sensum:pet will be within certification requirements for the existing standard pet ID microchip and will be capable of real time blood and ambient marker analysis, measuring glucose, cortisol, and ID up to eight times per day, while also allowing vets and owners to manually input additional information. Data collected by the device will then be analysed using machine learning algorithms, generating alerts for owners and vets when appropriate.

Sensum:pet will be Android and iPhone compatible and will provide the same functionality as leading health monitors, location devices and ID chip providers, with a battery life of approximately one month between charges.

Sensum:pet is fully GDPR compliant, and all associated data will be encrypted.

Appendix C. Questions Included in the Discussion Board

Barriers

1. A list of potential barriers to the use of sensor technology (consisting of an integrated ID and health microchip, as well as a wearable collar-based accelerometer) for early intervention and condition management within veterinary healthcare is detailed below. Please reorganise this list based on the perceived importance of each barrier (with the first barrier being the most important), adding any additional barriers that may not be included below.
   - **Cost**
   - **Legality**
   - **Time**
   - **Fear**
   - **Usefulness**
   - **Complexity**

2. A list of potential barriers to the use of sensor technology (consisting of an integrated ID and health microchip only) for early intervention and condition management within veterinary healthcare is detailed below. Please reorganise this list based on the perceived importance of each barrier (with the first barrier being the most important), adding any additional barriers that may not be included below.
   - **Cost**
   - **Legality**
   - **Time**
   - **Fear**
   - **Usefulness**
   - **Complexity**

3. A list of potential barriers to the use of sensor technology (consisting of wearable collar-based accelerometer only) for early intervention and condition management within veterinary healthcare is detailed below. Please reorganise this list based on the perceived importance of each barrier (with the first barrier being the most important), adding any additional barriers that may not be included below.
   - **Cost**
   - **Legality**
   - **Time**
   - **Fear**
   - **Usefulness**
   - **Complexity**

4. To overcome potential barriers, what features do you believe the sensor technology would need to offer?
5. Do you believe the benefits of using sensor technology within veterinary healthcare would outweigh potential barriers?

6. Do you believe your clients, or fellow dog/cat owners would react positively to the potential use of sensor technology for the early intervention and management of conditions? Please explain your answer.

Parameters

7. A list of parameters measurable using an integrated ID and health microchip, as well as a wearable collar-mounted accelerometer are detailed below. Please reorganise this list depending on your perceived importance of each parameter for the early intervention and management of canine/feline conditions (with the first parameter being the most important), adding any parameters which may not be included, which you feel could be measurable using the specified technology.
   - **Glucose**
   - **Cortisol**
   - **Temperature**
   - **Step count**
   - **Activity**
   - **Inactivity**

8. Would real time measurement of the above parameters solve any of the unmet needs you encounter as a veterinary professional or dog/cat owner? Please specify

9. Which canine/feline conditions do you believe would benefit from real time measurement of the above parameters?

10. Who would you expect to be the target audience for using such technology, for instance: veterinary surgeons, veterinary nurses, physiotherapists, hydrotherapists or dog/cat owners?

11. Who would you expect to be the target audience for interpreting the output of such technology, for instance: veterinary surgeons, veterinary nurses, physiotherapists, hydrotherapists or dog/cat owners?

12. Are you aware of any examples of similar technology being used in human medicine, which you feel could be transferred to use in veterinary healthcare?

Use of technology in veterinary therapeutics and the long-term monitoring of arthritis

13. The early detection and subsequent monitoring of a chronic condition using sensor technology would first require the identification of measurable, condition specific parameters. When considering the early detection and monitoring of canine osteoarthritis, please reorganise the below parameters in order of practicality for measurement (with the first parameter being the most practical), adding any additional parameters which may not be included.
    - **Walking speed**
    - **Stride length**
    - **Cadence**
    - **Gait cycle duration**
    - **Stride duration**
    - **Stride count**
    - **Stride frequency**
    - **Step duration**
    - **Step count**
    - **Step length**
    - **Step frequency**
    - **Stride phase**
    - **Stance phase**
    - **Swing phase**
    - **Footfall timing**
    - **Dorso-ventral/antero-posterior accelerations**
    - **Maximum/minimum head difference**
    - **Maximum/minimum pelvic difference**
    - **Gait cycle frequency**
    - **Duty Factor**
    - **Joint kinematics**
    - **Vertical ground reaction forces**

14. To measure the parameters specified in the previous question, the below technology can be used. Please reorganise this list in order of practicality for use (with number 1 being the most practical), adding any additional technology which you feel could also be used.
    - **Motion Capture**
    - **High speed cameras**
    - **Inertial sensors**
    - **Force platforms**
    - **Integrated health and ID microchips**

15. When diagnosing and monitoring canine osteoarthritis, (prioritising the experience of the affected dog), which technology listed in the previous question would you most like access to? (multiple technologies can be listed).

16. If access to the technology selected in the previous question was available, where would this technology be placed within the veterinary healthcare sector? For instance, a first opinion veterinary surgery, or a specialist clinic.

17. Who would you expect to use and interpret the results of such technology? For instance, veterinary surgeons, veterinary nurses, physiotherapists, or hydrotherapists.

18. Currently, what are your most common methods for diagnosing, treating and monitoring canine osteoarthritis?

19. With access to the technology identified in question 14, prioritising the outcome and experience of the affected dog, how do you believe your methods of diagnosing, treating, and monitoring canine osteoarthritis would change?

Appendix D. Materials for the Recruitment of Discussion Board Participants

Appendix E. Questionnaire Distributed During the First Round of the Delphi Consultation Process

Dear participant,

Thank you for your interest in completing this survey.

This questionnaire will form the first round of a Delphi Consultation process, used to collect expert opinions on an integrated ID and health chip for dogs and cats, until consensus is reached.

The questionnaire forms part of my PhD studies at Newcastle University, under the supervision of Prof Lucy Asher and Dr Matt Leach. Ethical approval has been granted under Ref: 15712/2021.

The content of the questionnaire will be dependent on the participant. For dog/cat owners, the questionnaire will comprise of a short demographics section, followed by a section covering the novel use of sensor technology in the healthcare of dogs and cats. For veterinary professionals, the aforementioned sections will be followed with an additional section, covering the methods for diagnosing and monitoring canine osteoarthritis.

For all participants, the questionnaire will take no longer than 20-30 minutes to complete, and progress can be saved throughout. Thank you in advance for completing this questionnaire.

Yours Sincerely,
Leanne Blake

This questionnaire is the first in a short series of surveys forming the Delphi Consultation process. Please provide an email address to which a subsequent survey can be sent.

____

Demographics Are you a veterinary professional?

- ○ Yes
- ○ No

Page Break

Demographics Please select your profession from the list below

- ○ Veterinary surgeon based in general practice
- ○ Veterinary surgeon based in a specialist/referral clinic
- ○ Veterinary nurse
- ○ Veterinary physiotherapist
- ○ Other (please specify) ____

Demographics How many years of post qualification experience do you have?

____

Page Break

Demographics Please indicate which animals you own.

- ○ Dog
- ○ Cat
- ○ Dog and cat

Page Break

Demographics Please indicate your gender by selecting all that apply.

- ○ Man
- ○ Woman
- ○ Non-binary
- ○ Not listed here
- ○ Prefer not to disclose
- ○ If you would like to expand on the gender options given above, or do not feel they represent you, please do so here ____

Page Break

Demographics Please specify your country of residence.

____

Page Break

Demographics Have you ever used a pet activity monitor?

- ◯ Yes - in vet practice
- ◯ Yes - with own pets
- ◯ No

Page Break

Introduction

Section one: Use of a novel sensor technology in the healthcare of dogs and cats.
The following section covers the use of a novel sensor device in the healthcare of dogs and cats. Please read the device description below before completing questions 1-18:

The device, Ora, will integrate an injectable ID chip, with a collar mounted accelerometer, from which combined data will be presented through a user-friendly interface.
It is intended that Ora will facilitate early condition identification and subsequent intervention, while supporting telehealth communications.

The chip component of Ora will be within certification requirements for the existing standard pet ID microchip and will also be capable of real time blood and ambient marker analysis, measuring glucose and cortisol up to eight times per day, while also allowing vets and owners to manually input additional information.

Data collected by the device will then be analysed using machine learning algorithms, generating pet health alerts for owners and vets when appropriate.

Ora will be Android and iPhone compatible and will provide the same functionality as leading health monitors, location devices and ID chip providers, with a battery life of approximately one month between charges.

Ora is fully GDPR compliant, and all associated data will be encrypted.

Page Break

Q1 The device is an integrated ID and health microchip, alongside a collar-mounted accelerometer, with the potential to measure the below parameters. Please indicate how useful you believe each parameter would be for the diagnosis and monitoring of canine/feline conditions.

	Not at all useful	Slightly useful	Moderately useful	Very useful
Glucose (blood sugar level)	○	○	○	○
Cortisol (stress hormone)	○	○	○	○
Body temperature	○	○	○	○
Daily step count	○	○	○	○
Activity/inactivity	○	○	○	○

Page Break

Q2 Who do you believe would be interested in using the proposed device?

- ☐ Veterinary surgeons
- ☐ Veterinary nurses
- ☐ Veterinary physiotherapists
- ☐ Veterinary hydrotherapists
- ☐ Dog/cat owners
- ☐ Other (please specify) ____

Page Break

Q3 How interested do you believe the selected roles would be in using the proposed device?

	Not at all interested	Somewhat interested	Interested	Very interested	Extremely interested
Veterinary surgeons	○	○	○	○	○
Veterinary nurses	○	○	○	○	○
Veterinary physiotherapists	○	○	○	○	○
Veterinary hydrotherapists	○	○	○	○	○
Dog/cat owners	○	○	○	○	○
Other	○	○	○	○	○

Page Break

Q4 Where do you believe the proposed device will most likely be used? Multiple options can be selected.

- ☐ First opinion veterinary surgery - general practice consult
- ☐ First opinion veterinary surgery - general practice specific clinic
- ☐ Specialist veterinary practice
- ☐ Paraveterinary (veterinary nurse clinic/physiotherapist/hydrotherapist)
- ☐ Non-clinical settings including the owners own home
- ☐ Other (please specify) ____

Page Break

Q5 Please indicate how beneficial you believe the proposed sensor would be when used in each of the selected settings.

	Not at all beneficial	Somewhat beneficial	Beneficial	Very beneficial	Extremely beneficial
First opinion veterinary surgery - general practice consult	○	○	○	○	○
First opinion veterinary surgery - general practice specific clinic	○	○	○	○	○
Specialist veterinary practice	○	○	○	○	○
Paraveterinary (veterinary nurse clinic/physiotherapist/hydrotherapist)	○	○	○	○	○
Non-clinical settings including the owners own home	○	○	○	○	○
Other	○	○	○	○	○

Page Break

Q6 What do you believe are the benefits to the use of sensor-based monitoring technologies? More than one response can be selected.

- ☐ Easier communication of pet symptoms between owners and vets
- ☐ Earlier detection of potential health issues
- ☐ More effective monitoring of ongoing health issues
- ☐ Ability to monitor health outside of practice
- ☐ Support through telemedicine
- ☐ More effective clinical practice
- ☐ Client engagement and practice loyalty
- ☐ Other (please specify) ____

Page Break

Q7 Please indicate the importance of each benefit selected.

	Not at all important	Somewhat important	Important	Very important	Extremely important
Easier communication of pet symptoms between owners and vets	○	○	○	○	○
Earlier detection of potential health issues	○	○	○	○	○
More effective monitoring of ongoing health issues	○	○	○	○	○
Ability to monitor health outside of practice	○	○	○	○	○
Support through telemedicine	○	○	○	○	○
More effective clinical practice	○	○	○	○	○
Client engagement and practice loyalty	○	○	○	○	○
Other	○	○	○	○	○

Page Break

Q8 Potential barriers to the use of the proposed sensor are listed, please select the barriers you perceive as being most important

- ☐ Cost of technology
- ☐ Legality
- ☐ Time taken to use/train on use of technology
- ☐ Concern about ability to use new technology
- ☐ Usefulness
- ☐ Complexity
- ☐ Integration with current systems
- ☐ Availability
- ☐ Lack of trust
- ☐ Implanting a (second) microchip
- ☐ Data security
- ☐ Animal's tolerance for wearing the device
- ☐ Potential destruction of the device during regular activity such as swimming
- ☐ Other (please specify) ____

Q9 Please indicate the importance of each barrier selected.

	Not at all important	Somewhat important	Important	Very important	Extremely important
Cost of technology	◯	◯	◯	◯	◯
Legality	◯	◯	◯	◯	◯
Time taken to use/train on use of technology	◯	◯	◯	◯	◯
Concern about ability to use new technology	◯	◯	◯	◯	◯
Usefulness	◯	◯	◯	◯	◯
Complexity	◯	◯	◯	◯	◯
Integration with current systems	◯	◯	◯	◯	◯
Availability	◯	◯	◯	◯	◯
Lack of trust	◯	◯	◯	◯	◯
Implanting a (second) microchip	◯	◯	◯	◯	◯
Data security	◯	◯	◯	◯	◯
Animal's tolerance for wearing the device	◯	◯	◯	◯	◯
Potential destruction of the device during regular activity such as swimming	◯	◯	◯	◯	◯

Other	○	○	○	○	○

Page Break

Q10 What features would a sensor-based monitoring system need to overcome potential barriers?

- ☐ Validated by veterinary research
- ☐ Integrated with existing practice management systems
- ☐ Interest/engagement of clients
- ☐ Understanding vets were involved in the development of the sensor
- ☐ Proof of data security
- ☐ Simple interface and practical system, which is easily available
- ☐ Low cost
- ☐ Used by trusted experts
- ☐ Proof of regulatory approval
- ☐ Reassurance the device would not harm the animal
- ☐ Durability of the wearable component
- ☐ Other (Please specify) ____

Page Break

Q11 To overcome the potential barriers of the proposed device, please indicate the importance each feature selected.

	Not at all important	Somewhat important	Important	Very important	Extremely important
Validated by veterinary research e.g. in published journals	○	○	○	○	○
Integrated with existing practice management systems	○	○	○	○	○
Interest/engagement of clients	○	○	○	○	○
Understanding vets were involved in the development of the system	○	○	○	○	○
Proof of data security	○	○	○	○	○
Simple interface and practical system which is easily available	○	○	○	○	○
Low cost	○	○	○	○	○
Used by trusted experts	○	○	○	○	○
Proof of regulatory approval	○	○	○	○	○
Reassurance the device would not harm the animal	○	○	○	○	○
Durability of the wearable component	○	○	○	○	○
Other	○	○	○	○	○

Q12 Below is a list of user interface features. Please select which features you believe would be most important when interacting with the proposed sensor

- ☐ Simple and intuitive design
- ☐ Quick navigation
- ☐ Concise icons and labels
- ☐ Responsiveness and short loading time
- ☐ Integration with existing systems
- ☐ Capacity for updates
- ☐ Undo and redo options
- ☐ Visibility of system status
- ☐ Accommodation of users with different skill levels
- ☐ Inclusion of tutorials and explanations
- ☐ Inclusion of a message interface between vets and animal owners
- ☐ Other (please specify) ________________________________

Page Break

Q13 Please indicate the importance of the user interface features selected.

	Not at all important	Somewhat important	Important	Very important	Extremely important
Simple and intuitive design	○	○	○	○	○
Quick navigation	○	○	○	○	○
Concise icons and labels	○	○	○	○	○
Responsiveness and short loading time	○	○	○	○	○
Integration with existing systems	○	○	○	○	○
Capacity for updates	○	○	○	○	○
Undo and redo options	○	○	○	○	○
Visibility of system status	○	○	○	○	○
Accommodation of users with different skill levels	○	○	○	○	○
Inclusion of tutorials and explanations	○	○	○	○	○
Inclusion of a message interface between vets and animal owners	○	○	○	○	○
Other	○	○	○	○	○

Q14 Below is a list of data presentation formats which could be implemented by the proposed device. Please indicate how convenient you find each format.

	Not at all convenient	Somewhat convenient	Convenient	Very convenient	Extremely convenient
Summary graphs	○	○	○	○	○
Tabulated data	○	○	○	○	○
Text summary	○	○	○	○	○
Raw data	○	○	○	○	○

Page Break

Q15 Do you believe the proposed device could support you in the diagnosis, treatment and management of health conditions in dogs and cats?

◯ Yes

◯ No

◯ Not sure

Page Break

Q15a Please elaborate on the ways the proposed device could support you in the diagnosis, treatment and management of health conditions in dogs and cats.

____

Page Break

Q15 Do you believe the proposed device could support you in the identification and management of health conditions in your dog/cat?

◯ Yes

◯ No

◯ Not sure

Page Break

Q15a Please elaborate on the ways the proposed device could support you in the identification and management of health conditions in your dog/cat.

____

Page Break

Q16 Do you believe the proposed device could benefit the relationship between vets and animal owners?

- ◯ Yes
- ◯ No
- ◯ Not sure

Page Break

Q17 How could the proposed device support the relationship between pets/owners and vets?

____

Page Break

Q18 If the proposed device was validated, with regulatory approval, would you be willing to use this technology?

- ◯ Yes
- ◯ No
- ◯ It depends (please provide further information below)

____

Page Break

Introduction **Section two: diagnosing and monitoring canine osteoarthritis**

The following section contains eight questions regarding the methods and technology used for diagnosing and monitoring canine osteoarthritis

Page Break

Q1 In general, how would you rate owner understanding of canine osteoarthritis?

- Very good
- Good
- Average
- Poor
- Very poor

Page Break

Q2 In general, how would you rate owner ability to recognise symptoms of canine osteoarthritis?

- Very good
- Good
- Average
- Poor
- Very poor

Page Break

Q3 Using the list included below, what are your most frequently used methods for detecting and monitoring canine osteoarthritis? More than one response can be selected.

- [ ] Visual assessment of dog's gait and ability to rise
- [ ] Owner's description of gait and behaviour changes
- [ ] Probing questions
- [ ] Clinical history
- [ ] Joint manipulation
- [ ] Response to treatment
- [ ] Radiography
- [ ] Palpation
- [ ] Observation of muscle wastage
- [ ] Appreciation of myofascial trigger points
- [ ] Observation of stance and posture
- [ ] Use of LOAD questionnaire

Page Break

Q4 Please indicate the usefulness and practicality of your most frequently used methods for diagnosing and monitoring canine osteoarthritis

	Usefulness					Practicality				
	Not at all useful	Somewhat useful	Useful	Very useful	Extremely useful	Not at all practical	Somewhat practical	Practical	Very practical	Extremely practical

Visual assessment of dog's gait and ability to rise										
Owner's description of gait and behaviour changes										
Probing questions										
Clinical history										
Joint manipulation										
Response to treatment										
Radiography										
Palpation										
Observation of muscle wastage										
Appreciation of myofascial trigger points										
Observation of stance and posture										

Use of LOAD questionnaire	○	○	○	○	○	○	○	○	○	○

Page Break

Q5 If you have any comments regarding the methods used for diagnosing and monitoring canine osteoarthritis, please leave them below.

____

Page Break

Q6 Using the list below, please select the gait parameters you believe could be measured to detect and monitor the early stages of canine osteoarthritis.

For definitions, please see the glossary.

Glossary

Walking speed – Distance travelled in meters per second (m/s).

Stride length - Distance between two successive pawprints for the same paw.

Cadence – Number of steps per minute.

Gait cycle duration - Time between two consecutive footfalls for the specific paw.

Stride duration – Time interval between two successive contacts between the paw and the floor.

Stride count - Number of consecutive strides within 60 seconds.

Step duration - Time between the paw leaving the floor and contacting the floor.

Step count - Number of steps in 60 seconds.

Step length – Distance between the final and initial contacts of the paw and floor.

Stance phase – Duration of time the paw is in contact with the ground.

Swing phase – Duration of time the paw is in the air.

Stride phase – The complete movement through swing and stance phase.

Footfall timing – Time when each paw contacts the ground, and the time each paw leaves the ground.

Maximum/minimum head difference - Difference in displacement between two lowest and two highest values of the head per stride.

Maximum/minimum pelvic difference - Difference in displacement between two lowest and two highest values of the pelvis per stride.

Gait cycle frequency – Number of gait cycles per second.

Duty Factor - Fraction of the gait cycle for which the foot is in contact with the ground.

Joint kinematics - Joint angles for hip, stifle, and tarsal joints, including range of motion.

Vertical ground reaction forces – Force exerted by the floor to the paw. Distribution of this force across the paw depends on the shape of the paw and the way it is placed on the floor.

- [ ] Walking speed
- [ ] Stride length
- [ ] Cadence
- [ ] Gait cycle duration
- [ ] Stride duration
- [ ] Stride count
- [ ] Step duration
- [ ] Step count
- [ ] Step length
- [ ] Stride phase
- [ ] Stance phase
- [ ] Swing phase
- [ ] Footfall timing
- [ ] Maximum/minimum head difference
- [ ] Maximum/minimum pelvic difference
- [ ] Gait cycle frequency
- [ ] Duty factor
- [ ] Joint kinematics

☐ Vertical ground reaction forces

Page Break

Q7
For each gait parameter selected, please indicate how practical these would be to measure, and how useful these measurements would be for the early detection and monitoring of canine osteoarthritis

	Usefulness					Practicality				
	Not at all useful	Somewhat useful	Useful	Very useful	Extremely useful	Not at all practical	Somewhat practical	Practical	Very practical	Extremely practical

Walking speed
Stride length
Cadence
Gait cycle duration
Stride duration
Stride count
Step duration
Step count
Step length
Stride phase
Stance phase
Swing phase
Footfall timing
Maximum/minimum head difference
Maximum/minimum pelvic difference
Gait cycle frequency
Duty factor

Joint kinematics	○	○	○	○	○	○	○	○	○	○
Vertical ground reaction forces	○	○	○	○	○	○	○	○	○	○

Page Break

Q8 If you have any comments regarding the parameters which could be measured to detect and monitor the early stages of canine osteoarthritis, please leave them below.

____

Page Break

Q9 Using the list below, please select the technology you believe could be used to detect and monitor the early stages of canine osteoarthritis. Multiple options can be selected.

- ☐ Motion capture
- ☐ High speed cameras
- ☐ Inertial sensors
- ☐ Force platforms
- ☐ X-ray

Page Break

Q10 Please indicate the usefulness and practicality of the technology selected for detecting and monitoring the early stages of canine osteoarthritis.

	Usefulness					Practicality				
	Not at all useful	Somewhat useful	Useful	Very useful	Extremely useful	Not at all practical	Somewhat practical	Practical	Very practical	Extremely practical
Motion capture	○	○	○	○	○	○	○	○	○	○
High speed cameras	○	○	○	○	○	○	○	○	○	○
Inertial sensors	○	○	○	○	○	○	○	○	○	○
Force platforms	○	○	○	○	○	○	○	○	○	○
X-ray	○	○	○	○	○	○	○	○	○	○

Page Break

Q11 If you have any comments regarding the technology that could be used to detect and monitor the early stages of canine osteoarthritis, please leave them below.

____

Appendix F. Questionnaire Distributed During the Second Round of the Delphi Consultation Process

Dear participant,

Thank you for your interest in completing this survey.

This questionnaire forms part of my PhD studies at Newcastle University, under the supervision of Prof Lucy Asher and Dr Matt Leach. Ethical approval has been granted under Ref: 15712/2021.

The following questionnaire forms the second round of a Delphi Consultation process, used to collect expert opinions on the use of sensor technology for diagnosing and monitoring canine osteoarthritis.

In the previous round, five questions reached consensus at a pre-defined level of 75%. The first section of this questionnaire details the responses submitted during the first round, in ranked order, giving you the opportunity to adjust the rank order where necessary.

The remaining three questions did not reach consensus at a pre-defined level of 75% and have been reformatted since the first round.

The questionnaire will take no longer than 15 minutes to complete, and progress can be saved throughout.

Thank you in advance for completing this questionnaire.

Yours Sincerely,
Leanne Blake

After analysing responses, an additional follow-up questionnaire may be required. Please provide your email address below if you are happy to participate in a follow-up survey.

____

Glossary For the following questions, please consider the definitions provided below:

Equipment
Force plate – A system designed to measure ground reaction forces.
High speed camera – A camera which operates at a high frame rate, enabling digital motion analysis.
Motion capture – Technology that digitally records patterns of movement, enabling gait analysis.
Sensors (accelerometers) – Small devices used to measure acceleration along a sensitive axis, providing insight into body movement.

Parameters
Walking speed – Distance travelled in meters per second (m/s).
Stride length - Distance between two successive footfalls for the same paw.
Cadence – Number of steps per minute.
Gait cycle duration - Time between two consecutive footfalls for the specific paw.
Stride duration – Time interval between two successive contacts between the paw and the floor.
Stride count - Number of consecutive strides within 60 seconds.
Step duration - Time between the paw leaving the floor and contacting the floor.
Step count - Number of steps in 60 seconds.
Step length – Distance between the final and initial contacts of the paw and floor.
Stance phase – Duration of time the paw is in contact with the ground.
Swing phase – Duration of time the paw is in the air.
Stride phase – The complete movement through swing and stance phase.
Footfall timing – Time when each paw contacts the ground, and the time each paw leaves the ground.
Maximum/minimum head difference - Difference in displacement between two lowest and two highest values of the head per stride.
Maximum/minimum pelvic difference - Difference in displacement between two lowest and two highest values of the pelvis per stride.
Gait cycle frequency – Number of gait cycles per second.
Duty Factor - Fraction of the gait cycle for which the foot is in contact with the ground.
Joint kinematics - Joint angles for hip, stifle, and tarsal joints, including range of motion.
Vertical ground reaction forces – Force exerted by the floor to the paw. Distribution of this force across the paw depends on the shape of the paw and the way it is placed on the floor.

The following questions will ask you to consider the **usefulness** of specified parameters, methods and technology, which could be used for diagnosing and monitoring canine osteoarthritis.

Q1 Below is a list of methods most frequently used by 56 experts when diagnosing canine osteoarthritis. Methods are in ranked order of **usefulness** and the level of agreement between experts is included as a percentage.
Methods which reached consensus at a pre-defined level of 75% in the previous round are highlighted in green, with the remaining methods highlighted in red.

Please indicate whether you agree with the ranked order. If you do agree with the order presented, please select the 'Yes' option at the end of the page.
If you do not agree with the order presented, please re-rank the methods, by selecting the method you wish to change by clicking on it and holding down the left mouse button while you drag it to a new position, before selecting the 'No' option at the end of the page.

______ Palpation (100%)
______ Appreciation of myofascial trigger points (100%)
______ Observation of muscle wastage (96.4%)
______ Response to treatment (96.3%)
______ Observation of stance and posture (95.5%)
______ Visual assessment of dog's gait and ability to rise (94.3%)
______ Joint manipulation (93.1%)
______ Clinical history (92.9%)
______ Radiography (90.5%)
______ Use of LOAD questionnaire (90%)
______ Probing questions (88%)
______ Owner's description of gait and behaviour changes (85.3%)

Q1 Do you agree with the ranked order presented above?

○ Yes

○ No

Q2 Below is a list of parameters which 56 experts believe could be measured when diagnosing and monitoring the early stages of canine osteoarthritis. Parameters are in ranked order of **usefulness** and the level of agreement between experts is included as a percentage. Parameters which reached consensus at a pre-defined level of 75% in the previous round are highlighted in green, with the remaining parameters highlighted in red.

Please indicate whether you agree with the ranked order. If you do agree with the order presented, please select the 'Yes' option at the end of the page.
If you do not agree with the order presented, please re-rank the parameters, by selecting the parameter you wish to change by clicking on it and holding down the left mouse button while you drag it to a new position, before selecting the 'No' option at the end of the page.

______ Step length (100%)
______ Stride count (100%)
______ Step count (100%)
______ Vertical ground reaction forces (94.4%)
______ Walking speed (94.1%)
______ Gait cycle duration (93.8%)
______ Duty factor (93.3%)
______ Joint kinematics (92.9%)
______ Stance phase (92.3%)
______ Stride phase (92.3%)
______ Maximum/minimum pelvic difference (90.9%)
______ Stride length (90.9%)
______ Stride duration (88.9%)
______ Footfall timing (88.2%)
______ Swing phase (87.5%)
______ Maximum/minimum head difference (87%)
______ Cadence (84.2%)
______ Step duration (83.3%)
______ Gait cycle frequency (71.4%)

Q2 Do you agree with the ranked order presented above?

◯ Yes

◯ No

Q3 Below is a list of technology which 56 experts believe could be used for diagnosing and monitoring the early stages of canine osteoarthritis. Technology is in ranked order of **usefulness** and the level of agreement between experts is included as a percentage. Technology which reached consensus at a pre-defined level of 75% in the previous round is highlighted in green, with the remaining technology highlighted in red.

Please indicate whether you agree with the ranked order. If you do agree with the order presented, please select the 'Yes' option at the end of the page.
If you do not agree with the order presented, please re-rank the technology, by selecting the option you wish to change by clicking on it and holding down the left mouse button while you drag it to a new position, before selecting the 'No' option at the end of the page.

______ X-Ray (100%)
______ High speed cameras (100%)
______ Motion capture (95.2%)
______ Sensors (92.9%)
______ Force plates (90.5%)

Q3 Do you agree with the ranked order presented above?

○ Yes

○ No

The following questions will ask you to consider the **practicality** of specified parameters, methods and technology, which could be used for diagnosing and monitoring canine osteoarthritis.

Q1 Below is a list of methods most frequently used by 56 experts when diagnosing canine osteoarthritis. Methods are in ranked order of **practicality** and the level of agreement between experts is included as a percentage. Methods which reached consensus at a pre-defined level of 75% in the previous round are highlighted in green, with the remaining methods highlighted in red.

Please indicate whether you agree with the ranked order. If you do agree with the order presented, please select the 'Yes' option at the end of the page. If you do not agree with the order presented, please re-rank the methods, by selecting the method you wish to change by clicking on it and holding down the left mouse button while you drag it to a new position, before selecting the 'No' option at the end of the page.

______ Use of LOAD questionnaire (100%)
______ Appreciation of myofascial trigger points (100%)
______ Observation of muscle wastage (96.4%)
______ Palpation (95.8%)
______ Clinical history (92.9%)
______ Response to treatment (92.6%)
______ Visual assessment of dog's gait and ability to rise (91.4%)
______ Observation of stance and posture (90.9%)
______ Joint manipulation (89.7%)
______ Probing questions (84%)
______ Owner's description of gait and behaviour changes (82.4%)
______ Radiography (76.2%) (

Q1 Do you agree with the ranked order presented above?

○ Yes

○ No

Q2 Below is a list of parameters which 56 experts believe could be measured when diagnosing and monitoring the early stages of canine osteoarthritis. Parameters are in ranked order of **practicality** and the level of agreement between experts is included as a percentage. Parameters which reached consensus at a pre-defined level of 75% in the previous round are highlighted in green, with the remaining parameters highlighted in red.

Please indicate whether you agree with the ranked order. If you do agree with the order presented, please select the 'Yes' option at the end of the page.
If you do not agree with the order presented, please re-rank the parameters, by selecting the parameter you wish to change by clicking on it and holding down the left mouse button while you drag it to a new position, before selecting the 'No' option at the end of the page.

______ Step count (100%)
______ Walking speed (94.1%)
______ Stride count (91.7%)
______ Stride duration (83.3%)
______ Step duration (83.3%)
______ Gait cycle duration (81.2%)
______ Step length (81.2%)
______ Cadence (78.9%)
______ Joint kinematics (78.6%)
______ Vertical ground reaction forces (77.8%)
______ Maximum/minimum head difference (73.9%)
______ Maximum/minimum pelvic difference (72.7%)
______ Stride length (72.7%)
______ Footfall timing (70.6%)
______ Stride phase (69.2%)
______ Swing phase (68.8%)
______ Duty factor (66.7%)
______ Gait cycle frequency (64.3%)
______ Stance phase (61.5%)

Q2 Do you agree with the ranked order presented above?

○ Yes

○ No

Q3 Below is a list of technology which 56 experts believe could be used for diagnosing and monitoring the early stages of canine osteoarthritis. Technology is in ranked order of **practicality** and the level of agreement between experts is included as a percentage. Technology which reached consensus at a pre-defined level of 75% in the previous round is highlighted in green, with the remaining technology highlighted in red.

Please indicate whether you agree with the ranked order. If you do agree with the order presented, please select the 'Yes' option at the end of the page. If you do not agree with the order presented, please re-rank the technology, by selecting the option you wish to change by clicking on it and holding down the left mouse button while you drag it to a new position, before selecting the 'No' option at the end of the page.

______ X-ray (75%)
______ Sensors (50%)
______ Motion capture (42.9%)
______ High speed cameras (40%)
______ Force plate (33.3%)

Q3 Do you agree with the ranked order presented above?

○ Yes

○ No

Introduction SECTION TWO

The following three questions did not reach consensus at a pre-defined level of 75% during the first round and have since been reformatted.

Q1 When diagnosing and monitoring the early stages of canine osteoarthritis, please indicate whether measurement of the parameter *gait cycle frequency* would be **useful**.

- ◯ Not useful
- ◯ Useful

Q2 When diagnosing and monitoring the early stages of canine osteoarthritis, please indicate whether you believe measurement of the following gait parameters would be **practical**.

	Not practical	Practical
Duty factor	◯	◯
Footfall timing	◯	◯
Gait cycle frequency	◯	◯
Maximum/minimum head difference	◯	◯
Maximum/minimum pelvic difference	◯	◯
Stance phase	◯	◯
Stride length	◯	◯
Stride phase	◯	◯
Swing phase	◯	◯

Q2 If you have any comments regarding the parameters which could be measured to diagnose and monitor the early stages of canine osteoarthritis, please leave them below.

____

Page Break

Q3 When diagnosing and monitoring the early stages of canine osteoarthritis, please indicate whether use of the following technology would be **practical**.

	Not practical	Practical
Force plate	○	○
High speed camera	○	○
Motion capture	○	○
Sensors	○	○

Q3 If you have any comments regarding the technology which could be used to diagnose and monitor the early stages of canine osteoarthritis, please leave them below.

____

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Appendix G. Summary of Kappa Values for Round One, Theme One Questions

Table 1G. Summary of Kappa values for round one, theme one questionnaire responses, highlighting the number of parameters to be ranked per question, as well as the number of participants within each stakeholder group that completed each question. Kappa values infer the level of interrater reliability, suggesting the extent to which two or more participants assigned the same rank to a particular parameter, whereby the values ranging from 0-0.2 indicate slight agreement, while values ranging from 0.21-0.4 indicate fair agreement (Landis & Koch 1977). Finally, P values indicate the statistical significance of the reported Kappa value.

Question	Participant	Number of parameters	Number of participants	Kappa Value	Z Value	P Value
1	Vet	5	48	0.025	1.88	0.060
	Owner	5	121	0.016	3.12	0.002
3	Vet	6	48	0.273	26.3	<0.001
	Owner	6	119	0.175	43.9	<0.001
5	Vet	6	48	0.164	16.3	<0.001
	Owner	6	111	0.112	25	<0.001
7	Vet	8	45	0.237	24.2	<0.001
	Owner	8	106	0.383	87.9	<0.001
9	Vet	14	45	0.16	19.7	<0.001
	Owner	14	104	0.192	57.2	<0.001
11	Vet	12	45	0.151	17.2	<0.001
	Owner	12	97	0.23	58.9	<0.001
13	Vet	12	44	0.16	17.9	<0.001
	Owner	12	93	0.111	26.6	<0.001
14	Vet	4	44	0.15	9.22	<0.001
	Owner	4	91	0.161	20.6	<0.001

Appendix H. Materials for The Recruitment of Sound Dogs

Newcastle University

chordata

Recruiting Science Dogs!

The Asher Behaviour Lab, based at Newcastle University are working in collaboration with Chordata to develop novel methods of monitoring canine activity, and we need your help!

The study will involve visiting Cockle Park Farm, where your dog will be fitted with small markers, and a collar mounted sensor, before being encouraged to demonstrate a range of behaviours including walking and playing, all while being recorded!

Participation will take around 1 hour, and the study will take place 3rd-7th July

If you're interested in taking part, please sign up using the QR code.
For further information, please email l.c.blake@newcastle.ac.uk

Appendix I. Questions Used to Screen Potential Participants, Adapted From the C-BARQ Questionnaire, Developed by Hsu and Serpell (2003)

1.What is your dog's name?

2.How old is your dog? Required to answer. Single line text.

3.How long have you had your dog? Required to answer. Single line text.

4.Is your dog neutered?

5.Please list the breed(s) of your dogRequired to answer. S

6.What is your dogs weight? (kg)Required to answer.

7.Is your dog vaccinated for DHLPP (vaccines for distemper, adenovirus/hepatitis, leptospirosis, parainfluenza, and parvovirus) AND is up-to-date on these vaccines?

8.Is your dog on any medication for pain or any condition that impacts reaction and perception?Required to answer.

9.Does your dog have any illness or injury that is painful, impairs their mental capacity, or impacts touch or vision? Ex. blindness, dementia, arthritis.Required to answer.

10.Does your dog readily accept food from strangers without showing aggressive behaviours? Aggressive behaviour around food may look like guarding the food with the body, staring hard, growling, lip curling or puckering, holding very still, or lunging.

Aggression

These next questions are about any situations where your dog may act aggressively:

Some dogs display aggressive behaviour from time to time. Typical signs of moderate aggression in dogs include barking, growling and baring teeth. More serious aggression generally includes snapping, lunging, biting, or attempting to bite.By selecting a number on the following 5-point scales (0= No aggression, 4= Serious aggression), please indicate your own dog's recent tendency to display aggressive behaviour in each of the following contexts. If the following contexts do not apply to your dog, please select 'N/A'

11.When verbally corrected or punished (scolded, shouted at, etc) by you or a household member.

12.When approached directly by an unfamiliar **adult** while being walked/exercised on a leash.

13.When approached directly by an unfamiliar **child** while being walked/exercised on a leash.

14.Toward unfamiliar persons approaching the dog while s/he is in your car (at the petrol station for example).

15.When toys, bones or other objects are taken away by a household member.

16.When bathed or groomed by a household member.

17.When an unfamiliar person approaches you or another member of your family **at home**.

18.When unfamiliar persons approach you or another member of your family **away from your home**.

19.When approached directly by a household member while s/he (the dog) is eating.

20.When his/her food is taken away by a household member.

21.When postal workers or other delivery workers approach your home.

22.When strangers walk past your home while your dog is outside or in the yard.

23.When an unfamiliar person tries to touch or pet the dog.

24.When joggers, cyclists, rollerbladers or skateboarders pass your home while your dog is outside or in the yard.

25.When stared at directly by a member of the household.

26.Toward unfamiliar persons visiting your home.

27.When stepped over by a member of the household.

28.When you or a household member retrieves food or objects stolen by the dog.

29.Are there any other situations in which your dog is sometimes aggressive? If so, please describe briefly

Fear

The following questions are about any situations where your dog may become scared or fearful:

Dogs sometimes show signs of anxiety or fear when exposed to particular sounds, objects, persons or situations. Typical signs of mild to moderate fear include: avoiding eye contact, avoidance of the feared object; crouching or cringing with tail lowered or tucked between the legs; whimpering or whining, freezing, and shaking or trembling. Extreme fear is characterised by exaggerated cowering, and/or vigorous attempts to escape, retreat or hide from the feared object, person or situation.Using the following 5-point scales (0=No fear, 4=Extreme fear), please indicate your own dog's recent tendency to display fearful behaviour in each of the following circumstances. If any of the following circumstances do not apply to your dog, please select 'N/A'.

30.When approached directly by an unfamiliar **adult** while away from your home.

31.When approached directly by an unfamiliar **child** while away from your home.

32.In response to sudden or loud noises (e.g. vacuum cleaner, car backfire, road drills, objects being dropped, etc.).

33.When unfamiliar persons visit your home.

34.When an unfamiliar person tries to touch or pet the dog.

35.In heavy traffic.

36.In response to strange or unfamiliar objects on or near the pavement (e.g. plastic bin bags, leaves, litter, flags flapping, etc.)

37.When examined/treated by a veterinarian.

38.During thunderstorms, firework displays, or similar events.

39.In response to wind or wind-blown objects.

40.When having nails clipped by a household member.

41.When groomed or bathed by a household member.

42.When having his/her feet towelled by a member of the household

43.Are there any other situations in which your dog is fearful or anxious? If so, please describe

Excitement

These next questions are about any situations where your dog may become overly excitable:

Some dogs show relatively little reaction to sudden or potentially exciting events and disturbances in their environment, while others become highly excited at the slightest novelty. Signs of mild to moderate excitability include increased alertness, movement toward the source of novelty, and brief episodes of barking. Extreme excitability is characterised by a general tendency to over-react. The excitable dog barks or yelps hysterically at the slightest disturbance, rushes towards and around any source of excitement, and is difficult to calm down. Using the following 5-point scales (0=Calm, 4=Extremely excitable), please indicate your own dog's recent tendency to become excitable in each of the following circumstances. If any of the circumstances do not apply to your dog, please select 'N/A'.

44.When playing with you or other members of your household.

45.When the doorbell rings.

46.Just before being taken for a walk.

47.Just before being taken on a car trip.

48.When visitors arrive at your home.

49.Are there any other situations in which your dog sometimes becomes over-excited? If so, please describe briefly:

Consent

Please answer the following questions. You can say no to any statement you disagree with and not all statements preclude participation in this study.

50.I have read and understood the study information provided on the previous pages. I am aware I can ask questions about the study and my questions (if asked) have been answered to my satisfaction.

51.I consent voluntarily to be a participant in this study. I understand that I can refuse to answer questions and that I can withdraw from the study at any time up until publication without having to give a reason.

52.I understand that the information I provide will be used for research within Asher Behaviour Lab at Newcastle University, and that the information will be anonymised.

53.I confirm that I am the owner/legal guardian of this dog and can make decisions about the dog.

54.Validation question: please select 'No'.

55.I understand that any personal information that can identify me, including email address, will be kept confidential and not shared with anyone outside the Asher Behaviour Lab and will be removed at publication.

56.I confirm I have pet insurance for my dog.

57.I give permission for the anonymised information to be deposited in a data archive so that it may be used for future research.

58.Please provide your email address (so we can send you further details on participation in the study

Thank you for completing the questionnaire

We will contact you shortly, using the email address provided, with further details. If you have any further questions regarding the study, then please email us at l.c.blake@newcastle.ac.uk

If you have any concerns or complaints regarding your participation in the study, please contact: sage.ethics@newcastle.ac.uk

If you have any concerns regarding the welfare of animals participating in the study, please contact: AWERB@newcastle.ac.uk

Appendix J. Materials for the Recruitment of Arthritic Dogs

A device for the early detection of osteoarthritis in dogs

The problem:

- Osteoarthritis is a chronic condition, affecting approximately 80% of dogs over 8 years old.
- The condition is often undiagnosed until unrelated veterinary appointments, posing a major health and welfare concern.
- Current methods of diagnosis can be both subjective and ineffective.

The Project:

- The project will explore the role of sensor technology in the early detection of canine osteoarthritis.

Newcastle University

Does your dog have osteoarthritis? Get involved!

As part of the study, a researcher will arrange to meet you and your dog on your regular walk, where a small, collar mounted accelerometer and GoPro video camera will record your dog's activity for up to half an hour.

If you would like further information on the study, or want your dog to be involved, please email: **l.c.blake@newcastle.ac.uk**

Appendix K. Questions used to Establish the Severity of Osteoarthritis in Prospective Participants. Questions Were Taken From the LOAD Questionnaire, Developed by Liverpool University

1.What is your dog's name?

2.What is the age of your dog?

3.What is the sex of your dog

4.What is the breed(s) of your dog?

5.How long has your pet been suffering with his/her mobility problems?

6.Has your dog been diagnosed as suffering from any other problems in addition to his/her orthopaedic disease?

7.If you answered yes to question 6, please specify any additional problems.

8.If you can, please list any medications that your dog is currently receiving, stating when he/she received the last dose of each.

9.In the last week, on average, how far has your dog exercised each day?

10.In the last week, how many walks has your dog had each day?

11.What type of exercise is this?

12.Are there any particular days of the week upon which your dog has significantly more exercise?

13.On what sort of terrain does your dog most often exercise?

14.At exercise, how is your dog handled?

15.Who limits the extent to which your dog exercises?

16.How is your dog's mobility in general?

17.How disabled is your dog by his/her lameness?

18.How active is your dog?

19.What is the effect of cold or damp weather on your dog's lameness?

20.To what degree does your dog show stiffness in the affected leg(s) after a 'lie down'?

21.At exercise, how active is your dog?

22.How interested is your dog in exercising

23.How would you rate your dog's ability to exercise?

24.What overall effect does exercise have on your dog's lameness?

25.How often does your dog rest (stop/sit down) during exercise?

26.What is the effect of cold/damp weather on your dog's ability to exercise?

27.To what degree does your dog show stiffness in the affected leg after a 'lie down' following exercise?

28.What is the effect of your dog's lameness on their ability to exercise?

29.I have read and understood the study information provided on the previous pages. I am aware I can ask questions about the study and my questions (if asked) have been answered to my satisfaction.

30.I understand that the information I provide will be used for research within Asher Behaviour Lab at Newcastle University, and that the information will be anonymised.

31.I understand that any personal information that can identify me, including email address, will be kept confidential and not shared with anyone outside the Asher Behaviour Lab and will be removed at publication.

32.I give permission for the anonymised information to be deposited in a data archive so that it may be used for future research.