THE MEASUREMENT OF KNEE JOINT POSITION SENSE

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Abstract

It is commonly stated proprioception or the perception of one's own limb position, movement and effort is reduced following an anterior cruciate ligament (ACL) injury. Therefore, this thesis begins with an analysis of all current literature on this topic in the form of a meta-analysis. It became clear that the methods used to measure knee proprioception were very inconsistent and did not appear to provide normative levels of knee proprioception making it very difficult to syntheses results. This led to the thesis main objectives. The first study provided a reliable and valid method of knee joint position sense (JPS), the static component of proprioception, based on previous JPS protocols. This method was then used in the remaining studies to consider normative values of a UK population, the effect of ACL injury in both non-athletic and elite athletic populations, the effect of knee injuries (not including ligament damage) and the effect of fatigue on knee JPS. The most appropriate clinical method of measuring knee JPS using image capture as covered in this thesis was in a sitting position, from full extension in to 60-90 degrees of flexion and from 90 degrees of flexion in to 30-60 degrees of extension. Age, mass, height, BMI, activity level, knee condition (other than ligament injury) or fatigue did not appear to significantly affect knee JPS in an uninjured population. However, both non-athletic and elite athletic populations with previous ACL injury demonstrated significantly worse knee JPS when compared to controls. In conclusion, it would appear the only knee condition that reduces joint position sense ability is ACL injury. Although, it may also be possible the method is not sensitive enough to measure subtle changes in JPS in other populations due to large measurement error values. In the future it may not be necessary to place importance on knee joint position sense as it either may not be impacted by any injury other than ACL damage, or the methods used to collect JPS are not sufficient in measuring changes during rehabilitation. Additionally, it is important researchers consider the relationship between knee JPS and functional movements.

Chapter 1 Introduction

1.1 Anterior Cruciate Ligament (ACL) Injury and Knee Proprioception

It is estimated 250,000 people injure their anterior cruciate ligament each year in the United States alone (Hewett *et al*., 2007a). One potential mechanism of this injury is reduced knee proprioceptive ability (Hewett *et al*., 2007a). Further, once the patient has completed rehabilitation, perhaps after reconstructive surgery, evidence suggests a proprioceptive deficiency in the knee is still present (Bonfim *et al*., 2003, Roberts *et al*., 2000, Rehm *et al*., 1998, Barrett 1991a, Carter *et al*., 1997). Therefore clinical practitioners use '*proprioceptive exercises*' to attempt to regain pre-injury levels of knee proprioception (Swanik *et al*., 1997, Ingersoll *et al*., 2008). However, the success of this treatment is unclear in the literature.

There is strong evidence to support the presence of mechanoreceptors in the anterior cruciate ligament tissue (Barrack *et al*., 1994). Hence it is intuitive to assume following an injury to this ligament, knee proprioception may be reduced due to the loss of activated mechanoreceptors in the knee joint during motor tasks. Indeed, there is a plethora of literature to support this viewpoint (for example Fischer-Rasmussen and Jensen, 2000, Fremerey *et al*., 2000, Ozenci *et al*., 2007, Mir *et al*., 2008 and Angoules *et al*., 2011). However, there is also research to counter this theory (for example Remedios *et al*., 1998, Good *et al*, 1990, Harter *et al*., 1992, Dvir *et al.,* 1988, Fischer-Rasmussen *et* al., 2001, Jensen *et al*., 2002, Co *et al*., 1993, Friden *et al*., 1996), the belief being that a proprioceptive deficit is not present following an ACL injury as other mechanoreceptors in and around the knee joint, particularly the surrounding musculature, may compensate for the loss of ACL afferent information (Beard and Refshauge 2000). The reason for the contradictions in research findings may be due to the vast range of knee proprioception measurement techniques used in ACL deficient population studies. However, without a validated, reliable measure of knee proprioception it is impossible to make a satisfactory conclusion on ACL injury and knee joint proprioception.

1.2 Proprioception

The subject of proprioception is steeped in history. For at least 400 years researchers have investigated how people are able to perceive and accurately control limb movements without visual input (Proske, 2006). Proprioception is critical for normal motor control and is therefore a key component of musculoskeletal rehabilitation. However, despite the obvious importance there is no universally accepted definition of proprioception (Lephart *et al*.,

2000). Sherrington (1906a) first published the word proprioception describing it as "*a deep field of receptors in which stimuli are traceable to actions of the organism*" (p.472). It is believed Sherrington constructed the word from the Latin "proprius" (one's own) and "reception" (receives). Clinicians have stated global proprioception as "*a specialized type of the sense of touch*" (Barrack *et al*., 1994, p.19) and "*the sense of position and movements of the limb*" (Grigg, 1994, p. 2) and it is thought to be "*...used to reference the afferent information arising from proprioceptors*" (Riemann and Lephart, 2002a p.72). However, if considered in more detail proprioception can be divided into two key aspects of joint homeostasis; joint kinaesthesia (the dynamic sense of movement including joint acceleration, force and velocity) and joint position sense (the static sense of movement) (Ogard, 2011).

Important spatial and temporal afferent information is provided by specialised '*proprioceptors*' or mechanoreceptors located in and around joints (Hogervorst and Brand 1998). These receptors include muscle spindles, Golgi tendon organs, ruffini nerve endings, pacinian corpuscles, Meissen's corpuscles and Merkel's discs (Richards and Selfe, 2012). Receptor afferent information is transmitted by transforming the mechanical energy caused by physical deformation of the joint and muscles to electrical energy of nerve action potential (Stillman, 2002). This information is transmitted to the central nervous system (CNS) and in turn organised and managed in various higher order areas (Biedert, 2000). For example balance and posture are organised at the brain stem but some proprioceptive information is organised at higher levels such as the cerebral cortex and the cerebellum (Biedert, 2000). Motor control commands are sent to relevant muscles around the joint to ensure co-ordinated, effective movement (Riemann and Lephart 2002b). It is clear proprioception has an important role in normal efficient movement therefore clinicians require valid and reliable measurement tools to monitor joint proprioception in patients.

1.3 Knee Proprioception

The knee is a complex multi-directional articulation (Dye and Vaupel, 2000) and various types of mechanoreceptors have been located in and around the joint that are believed to contribute to knee joint homeostasis (Johansson *et al*., 1991a). Indeed the majority of research has provided evidence of a sensory role for the joint's cruciate ligaments (Friden *et al*., 2001). The anterior cruciate ligament may have up to 2.5% of neural elements consisting of ruffini nerve endings, Golgi tendon organs and pacinian corpuscles (Jennings, 1994). The

posterior cruciate ligament also contains these types of mechanoreceptors (Katonis *et al.*, 1991). In addition, other areas of the knee joint including the medial and lateral collateral ligaments and menisci all contain types of mechanoreceptors and hence may play a role in joint proprioception (Solomonow and Krogsgaard, 2001, Pitman *et al.*, 1992). The presence of mechanoreceptors throughout the knee joint suggests proprioceptive afferent information is not only provided by the supporting musculature as once thought (Scott and Loeb, 1994). It is most likely knee joint homeostasis is achieved by accumulation of all mechanoreceptor information, defined as the "*final common output theory*" (da Fonseca *et al.*, 2004). The majority of tissues in the knee joint and its surrounding muscles provide important afferent information on knee position and movement, therefore it is critical clinicians can measure knee joint proprioception in order to accurately evaluate proprioceptive rehabilitation and pre-screening programmes aimed at preventing knee injury.

1.4 Knee Proprioception Measurement Techniques

There have been a variety of approaches to knee proprioception measurement including investigation of sensory evoked potentials (Courtney *et al.*, 2005), gait analysis adaptations following injury (Devita *et al.*, 1998), electromyography of lower extremity muscles (Houck *et al.*, 2007), postural control (Wikstrom *et al.*, 2006) and ligament-muscle protective reflexes (Beard *et al.*, 1993). However, the two most common protocols in a clinical setting are threshold to detect passive motion (TTDPM) and joint position sense (JPS) (Riemann *et al.*, 2002c). In threshold to detect passive motion protocols the participant is most often seated and the leg is passively moved, the participant must then indicate, typically via a hand switch, the detection of this movement (Beynnon *et al.*, 2000). This is a measure of dynamic proprioception or kinaesthesia. Joint position sense protocols involve measurement of an error angle, taken from the difference between a target knee angle set by the researcher and a reproduced knee angle completed by the participant (Beynnon *et al.*, 2000). This is a measure of static proprioception. Although it is agreed these are the two most commonly used knee proprioception measurement techniques, there is no consistency in the protocol details. For example researchers and clinicians have used a variety of equipment, angular velocities and displacements, target angles, knee movements and participant positions in knee proprioception measurement. Furthermore, there is no large evidence base which recommends the necessary number of trials for JPS testing. This is not an extensive list of decisions to be made prior to data collection and therefore it is perhaps not surprising a

consensus on the most appropriate method has not been agreed. There is also a shortage of reliability and validity analysis of knee proprioception measurement techniques. Any, or all of these variables may impact on the measurement of knee proprioceptive ability. As previously stated, it is imperative clinicians can evaluate knee proprioceptive ability effectively and therefore a standardised method of knee proprioception must be established.

1.5 Age and Knee Proprioception

An increase in age is perhaps inevitably correlated to a decrease in certain musculoskeletal and neurological systems (Gilsing *et al*., 1995). Therefore it is perhaps no surprise research has identified a proprioceptive decline with an increase in age. The results of cross-sectional research evidence shows reductions in both static (JPS) and dynamic (TTDPM) proprioceptive ability with older populations (Kokmen *et al*., 1978, Pai *et al*., 1997, Barrett *et al*., 1991b, Kaplan *et al*., 1985, Petrella *et al*., 1997, Hurley *et al*., 1998). This has been explained using theory on both peripheral and central adaptations. At the mechanoreceptor level, joint stiffness increases with age (Miwa *et al*., 1995). This is because of age adaptations in the muscle receptors; the receptors diameters reduce (Herter *et al*., 2014) and the capsular thickness increases (Swash and Fox, 1972, Mynark and Koceja, 2001). This can create a reduction in sensitivity of muscle spindles and hence proprioception (Herter *et al*., 2014). Furthermore, the composition of muscle spindles can change which again contributes to desensitisation of the muscle spindles (Suetterlin and Sayer, 2014) and also the total number of effective mechanoreceptors reduces (Shaffer and Harrison, 2007, Aydoğ *et al*., 2006, Iwasaki *et al*., 2003).

Dendrites receive and relay stimuli between neurones and thus are critical to efficient motor control (Lundy-Ekman, 2013, McBean and van Wijck, 2013). At the central level, evidence has suggested the dendrite system is less effective in older patients (Ribeiro and Oliveira, 2010). Furthermore, the nerve conduction velocity decreases, along with a reduction in the number of motor units in adults over 60 years old (Campbell *et al*., 1973). All potential age related declines may reduce proprioceptive ability (Barrack *et al*., 1993, Yan and Hui-Chan, 2000). However, there is no normative data available that considers a range of adult ages across a healthy population. This is needed to inform clinicians and their treatment of proprioceptive deficits.

1.6 Gender and Knee Proprioception

The majority of clinical practitioners will be aware of the difference in ACL injury rates between men and women; women appear to have a higher risk of ACL injury than men (Arendt *et al*., 1999). However, there is limited research that considers the effect of gender on proprioception and hence if this indeed may be a contributing factor to the increased rate of ACL injury in women. Both Rozzi *et al*., (1999a) and Nagai *et al*., (2012) reported some initial reports of a female reduction in knee proprioception. Furthermore authors have considered the effect of the menstrual cycle on proprioception, the theory being the increase in oestrogen interacts with neurotransmitters in the brain which may improve central processing of afferent information (Daniusevičiūtė et *al*., 2012). However, researcher findings are inconsistent (Fridén *et al*., 2006, Hertel *et al*., 2006). Therefore, there is a need for a large scale normative study on knee proprioception that considers any potential effects of gender.

1.7 Body Mass Index and Knee Proprioception

Body mass index (BMI) is a standard measure of mass of a patient with concurrent consideration of height (World Health Organisation, 2000). The effect of BMI on knee proprioception has rarely been considered in the literature. Paschalis *et al*., (2013) reported proprioceptive deficiencies in overweight and underweight participants compared to a lean control group. Also, Kaya *et al*., (2014) compared overweight patients with pathology to uninjured overweight controls and reported pathology reduced knee proprioceptive ability. However, to the author's knowledge this is the full extent of the literature on BMI and proprioception. There are many detrimental consequences of becoming overweight; therefore it may be a reduction of proprioception is also one of these negatives. Clinicians should be aware of the effects of BMI on proprioception to inform their practice. However, more evidence is required in this area.

1.8 Physical Activity and Knee Proprioception

In contrast to gender and BMI, the effects of physical activity on proprioception have been well researched in recent years. Regular physical activity has many health benefits and the majority of research would suggest an enhanced proprioceptive ability is one of those benefits. Many studies consider the effects of regular physical activity and proprioception using elderly populations (Tsang and Hui-Chan, 2003, 2004, Li *et al*., 2008a, 2008b, Xu *et al*., 2003, Petrella *et al*., 1997, Ribeiro and Oliveira, 2010). The type of exercise

implemented in this research ranges from Tai Chi, golf, swimming, running and strength training. Results are of the same consensus; regular physical activity appears to heighten knee proprioception. In particular with the elderly groups, regular exercise may indeed attenuate the age related decline in proprioception. This is explained by exercise induced adaptations at both peripheral and central areas.

It is thought the latency of the stretch reflex is reduced and the amplitude of the stretch reflex is increases as a result of regular exercise (Hutton and Atwater, 1992). The repetitive nature of exercise may also improve the effectiveness of the gamma motor neuron route (Ribeiro and Oliveira, 2010). This also improves central processing of afferent information (Tsang and Hui-Chan, 2003). Furthermore exercise increases body temperature which has been shown to improve the effectiveness of cutaneous receptors up to temperatures of 37°C (Green, 1977, Gescheider *et al*., 1997). Therefore regular exercise is thought to improve knee proprioception.

Regular physical activity or training is critical to elite athletic populations. It follows that elite athletes may have enhanced knee proprioception. Indeed, much research provides support for this hypothesis, for example early work by Lephart *et al*., (1996) and Barrack *et al*., (1984a, 1984b) reported increased proprioceptive ability in ballet dancers and gymnasts. Other research has replicated this finding with American footballers and archers (Euzet and Gahery 1995) soccer players (Muaidi *et al*., 2009) swimmers and badminton players (Han *et al*., 2013a and Waddington *et al*., 2013). The reasons for this may be divided into two areas: innate characteristics (Euzet and Gahery, 1995) and the effects of long term training (Ashton-Miller *et al*., 2001). Elite athletes may be born with superior physiological and neural systems that may enhance proprioception. This may further be enhanced by improvements in central processing of afferent information that may occur during training (Meeuwsen *et al*., 1993). However, the elevated performance of regular exercisers and elite athletes needs to be confirmed using reliable and valid knee proprioception testing.

1.9 Peripheral/ Muscular Fatigue and Knee Proprioception

Peripheral or muscular fatigue references the effects of fatigue below the neuromuscular junction, in the muscle fibres and specifically to the adaptations in the contractile mechanisms of muscle (Hiemstra *et al*., 2001). The outcome of peripheral or muscular

fatigue is typically a decrease in the capacity to produce muscular force (Enoka and Duchateau, 2008). The effect of peripheral or muscular fatigue on proprioception has been well considered in the literature (Allen and Proske, 2006, Rozzi *et al*., 1999b, Torres *et al*., 2010, Skinner *et al*., 1986a, Gear, 2011, Ju *et al*., 2010, Miura *et al*., 2004, Allen *et al*., 2010, Ribeiro *et al*., 2007, Stillman *et al*., 1999, Ribeiro *et al*., 2011, Paschalis *et al*., 2007, 2008, 2013, Marks and Quinney 1993, Dieling *et al*., 2014). This research provides information on a proprioceptive decline following a bout of maximum exercise to fatigue levels (Torres *et al*., 2010, Allen *et al*., 2010, Ribeiro *et al*., 2011, Gear, 2011). This may be attributed to impaired excitation of the motor units (Rozzi *et al*., 2000), an increase in knee laxity (Changela *et al*., 2012) and an increase in pain (Fortier and Basset, 2012).

However, conversely authors have published evidence that peripheral or muscular fatigue fails to reduce knee proprioceptive ability (Miura *et al*., 2004, Stillman *et al*., 1999, Dieling *et al*., 2014, Marks and Quinney, 1993). The contrariety of research may be due to inconsistencies in the fatiguing protocol and knee proprioception measurement. Therefore it is still unclear how peripheral or muscular fatigue impacts proprioceptive ability.

1.10 Osteoarthritis and Knee Proprioception

Osteoarthritis in the most common type of arthritis (Pai *et al*., 1997) and the knee joint is the most common location for the disease (Sharma *et al*., 1997). Unfortunately, the pathology typically causes a reduction in knee joint stability and therefore potentially a loss of knee proprioceptive ability (Collier *et al*., 2004). This result has been demonstrated using both knee kinaesthesia (Lund *et al*., 2008) and knee joint position sense (Segal *et al*., 2010). It is thought this can be attributed to impaired articular mechanoreceptors and hence modulated afferent discharge, reduced gamma motor neurone activity and inflammation of the joint (Knoop *et al*., 2011). However, as stated in previous sections, the measurement of knee proprioception is far from consistent. Therefore clinical practitioners should generalise current research with caution.

1.11 Thesis Aims and Objectives

The global aim of this thesis can be divided into two sub-sections. The first aim involves measurement; to find the optimal condition to record knee joint position sense ability. The

second aim involves implementation of this tool to report the effects of various independent variables on knee joint position sense ability. The different components of each aim are provided below:

Methodological Aims

To establish a measurement technique that provides the best representation of knee joint position sense ability.

To establish a reliable, consistent and sensitive measurement of knee joint position sense.

To establish a valid measurement technique of knee joint positioning.

To establish the number of trials required for consistent knee joint position sense.

Population Group Aims

To collect normative knee joint position sense from a representative sample of the UK population.

To consider the effects of age, gender, BMI, physical activity and self-reported knee condition on knee joint position sense.

To compare the knee joint position sense of anterior cruciate ligament deficient patients (both non-athletic and elite athletic) to an uninjured matched control group.

To compare the knee joint position sense of patients with any other knee injury (not including ligament damage e.g. OA) to an uninjured matched control group.

To consider the effect of peripheral fatiguing exercise on knee joint position sense.

Chapter 2 - Literature Review

2.1.1 The effect of Anterior Cruciate Ligament Injury on Knee Proprioception

The ACL is the most commonly injured knee ligament (Miyasaka *et al.*, 1991). Hewett (2007a) states potentially 250,000 individuals will suffer an ACL injury, with approximately 50,000 needing knee surgeries (Miyasaka *et al.*, 1991) each year in the United States alone. Injuries to the ACL are career threatening for sports professionals and even when rehabilitation is completed, secondary injury problems are common place (Lephart *et al.*, 2000). There is a significantly greater risk of suffering osteoarthritis in the damaged limb, occurring at 10 times a greater rate in ACL-injured athletes, as well as higher risk of injury to the uninjured knee (Bahr and Krosshaug, 2005, Hewett et al., 2006, Johansson *et al.*, 2000). Therefore, it is important to develop effective treatments and preventative strategies for ACL injury.

Evidence suggests an ACL injury significantly reduces the number of effective mechanoreceptors in the ligament (Barrack *et al.*, 1994). Typical surgical practice is to reconstruct and replace the damaged ligament tissue with tendon tissue, which again reduces the number of working mechanoreceptors (Hewett, 2007a).

Mechanoreceptors provide important afferent information regarding position (static) and movement (dynamic) to the central nervous system for processing, this is known as proprioception (Lephart *et al.*, 2000). Therefore it follows that such injuries can be detrimental to proprioception of the knee. The subject of proprioception is steeped in history. For at least 400 years researchers have been investigating how people are able to perceive and accurately control limb movements without visual input (Proske, 2006). Proprioception plays a critical role in normal human performance (Riemann and Lephart, 2002a, 2002b, Stillman, 2002, Barrack and Munn, 2000). Deficits may lead to abnormal movement patterns which may lead to knee misalignment then to other problems such as osteoarthritis (Lephart *et al.*, 2000). Physiotherapists and other clinical practitioners have therefore used measurements of proprioception in training and rehabilitation strategies to inform their practice (Hewett et *al.*, 2007b, Ogard, 2011, Stillman, 2000). It is common place for physiotherapists to include proprioceptive exercises in rehabilitation following an ACL injury (Perrin and Irrgang, 2000).

However, research into the effects of ACL injury on knee proprioception has yielded conflicting results (Beard and Refshauge, 2000). It is possible clinicians are treating an ACL

injury with proprioceptive exercises without significant evidence this proprioceptive deficit exists. Therefore a meta-analysis was completed to assess the effects of ACL injury on knee proprioception (see appendix 1a, 1b, 1c). This meta-analysis will be described in the next section.

2.1.2 The effects of Anterior Cruciate Ligament Injury on Static and Dynamic Knee Proprioception

Relph *et al*., (2014) revealed six studies of sufficient quality and low risk of bias to consider the effect of ACL injury on joint position sense (see table 1 for details). These studies were selected using a meta-analysis protocol. No review protocol exists for meta-analysis of descriptive data, thus the PRISMA guidelines on meta-analysis were followed as far as was practicable for the type of data concerned (http://www.prisma-statement.org/statement.htm). The following electronic databases were accessed from their inception to September 2013: AMED, CINAHL, PubMed, Medline, PeDro, Sports Discus and the Cochrane Library. Primary journals in the field; The Knee, American Journal of Sports Medicine and the British Journal of Sports Medicine were also manually searched, as were the reference lists of all selected studies to ensure the search was comprehensive. Key terms were: anterior cruciate ligament, proprioception, postural sway, joint position sense, balance, equilibrium or posture using the Boolean operator "OR". Limits of the search were: English language studies (none of the researchers spoke foreign languages); human studies, adult participants and peer reviewed published full access articles. Unpublished literature and trial registries of current studies were not included in the search. Studies were eligible for inclusion if they 1) investigated proprioception of the knee following ACL injury (conservatively managed or reconstructed) 2) recruited adults (over 16 years) with an ACL injury, including participants with ACL injuries combined with meniscus and/ or collateral ligament damage and 3) included a primary outcome measure of knee proprioception measured by mean angle of error in degrees.

The primary outcome measure could take two forms; studies measuring knee kinaesthesia used the TTDPM method where the mean angle of error was defined as *the difference in degrees from initiation of motion and the participant's perception of motion* and studies measuring JPS utilising an index angle matching method in which the mean angle of error was defined *as the difference in degrees between the target angle and the angle reproduced by the participant*. The type of control measure (the participant's contralateral leg or the leg

of an external matched control) was also collected along with the corresponding data. The search results were merged using reference management software (Endnote X6) and duplicates removed. The titles and abstracts were screened and articles which obviously did not meet the selection criteria removed.

Table 1: Characteristics of the articles included in the meta-analysis (Relph *et al*., 2014).

Study	Participants	Age, mean (SD) and Gender ACL patients	Age, mean (SD) and Gender Controls	Equipment	Knee ROM	Method of measuring proprioception
Barrack *et al*., (1989)	11 ACL-D 10 Controls.	25 (NP) years 9 men, 2 women	25 (NP) years NP	Purpose built proprioception device.	From a starting angle of 40° at an angular velocity of 0.5°/s.	TTDPM - Mean angle of error in degrees from 10 trials randomly assigned to flexion or extension
Fischer-Rasmussen and Jensen (2000)	20 ACL-D 18 ACL-R 20 Controls	ACL-D 27(5) years 11 men, 9 women ACL-R 27(5) years 9 men, 9 women	27(4) years 11 men, 9 women (Plus uninjured knees of patients)	Purpose built proprioception device.	From a starting angle of 25° flexion to 15, 20, 25, 30, 35 or 60° flexion to full extension.	JPS (passive positioning then active repositioning task) – Mean angle of error in degrees from 20 trials randomly assigned to target angles.
Fremerey *et al*., (2000)	10 ACL-D 20 ACL-R 20 Controls	ACL-D 22.7(3.2) years 7 men, 3 women ACL-R 28.4(4.4) years 13 men, 7 women	26.4(4.8) years 13 men, 7 women (Plus uninjured knees of patients)	Purpose built proprioception device.	From a starting angle of 0° to random target angles in 3 intervals; extension 0-20° , mid-range 40-60° and flexion 80-100°. All passive motion was set at 0.5°/s.	JPS (passive positioning then passive repositioning task) – Mean angle of error in degrees from trials randomly assigned from the extension range, mid-range and flexion range.
Ozenci *et al*., (2007)	20 ACL-R (auto-graft) 20 ACL-R (allo-graft) 20 ACL-D	ACL-D 29.0(5.4) years 18 men, 2 women ACL-R Auto – 29.5(6.9) years 20 men	27.6(2.6) years 17 men, 3 women (Plus uninjured knees of patients)	Cybex Dynamometer	JPS - From full extension to flexion (no further details given). TTDPM - From 15° flexion to either flexion or extension at an angular velocity of 1°/s.	JPS (passive positioning then active repositioning task) – Mean angle of error in degrees from 10 trials. TTDPM - Mean angle of error in degrees from 10 trials randomly

	20 Controls	Allo – 30.2(4.6) years 16 men, 4 women				assigned to either flexion or extension.
Angoules *et al*. (2011)	20 ACL-R (hamstring)	16 men, 4 women	N/A	Con-Trex Dynamometer	JPS – From full extension (0°) to flexion angles of 15, 45 & 75°.	JPS (passive positioning then active repositioning task) – Mean angle of error in degrees from three trials.
	20 ACL-R (patella tendon)	18 men, 2 women				
Mir *et al*. (2008)	12 ACL-R 12 Controls	23(4.75)years 12 men	22(4.35) years 12 men (Plus uninjured knees of patients)	Digital camera, markers.	From a starting angle of 60° flexion to 30° flexion and from a starting angle of 0° flexion to 30° flexion. All motion was at an angular velocity of 10°/s.	JPS (active positioning then active repositioning task) - Mean error angle in degrees over 3 trials.

ACL-D: Patients with an ACL deficiency, ACL-R: Patients with a reconstructed ACL, TTDPM: Threshold to detect passive motion, JPS: Joint position sense. NP: Not Provided, NA: Not applicable.

The full text of the remaining studies was then checked against the selection criteria. Studies with outcome data that did not meet our criteria were excluded at this stage. The selection of appropriate articles was agreed through discussion between two of the researchers and a third party was available to arbitrate if necessary.

The methodological quality of the studies that met the selection criteria was appraised by two of the research team independently to identify studies that had a low risk of bias. There is no established tool to assess the methodological quality of descriptive studies, therefore we amended a quality assessment tool previously developed and used by the researcher team (Herrington and Fowler, 2006). This tool considered eight potential sources of bias; confirmation of ACL deficiency, representation of population, representation of sample, homogeneity of participants, sample size, study design, assessor blinding / bias, statistical analysis (see appendix 1b and Table 2). The better the source of bias was addressed, the more points were awarded. Summating the scores for items on the assessment gave a maximum score of 88. The methodological quality scores were arbitrarily, but logically, grouped as 'poor' (a score of less than 29/88), 'moderate' (a score of 30-58/88) or 'good' (a score of 59+/88). Studies of moderate to good quality (that is, 30–88/88) were selected as providing data of sufficient low risk of bias to enter in to the meta-analysis.

Table 2: Methodological quality score for each of the articles included in the meta-analysis

Scoring Section (maximum score)	Barrack *et al*., (1989)	Fischer-Rasmussen & Jensen (2000)	Fremerey *et al*., (2000)	Ozenci *et al*., (2007)	Angoules *et al*., (2011)	Mir *et al*., (2008)
Confirmation of ACL Deficiency (3)	3	1	3	1	3	0
Representation of Population (19)	9	8	10	14	13	10
Representation of Sample (5)	3	0	3	3	3	0
Homogeneity of Participants (13)	5	11	11	7	4	11
Sample Size (25)	3	9	7	9	6	4
Study Design (4)	1	1	1	1	4	1
Assessor Blinding / Bias (5)	5	0	0	0	5	0
Statistical Analysis (14)	1	1	4	3	14	9
Total (88)	**30**	**31**	**39**	**38**	**52**	**35**
Quality Level	**Moderate**	**Moderate**	**Moderate**	**Moderate**	**Moderate**	**Moderate**

Note: Studies were grouped in to poor (a score of less than 29/88), moderate (a score of 30-58/88) or good (a score of 59+/88) studies based on their final methodological quality score.

Studies that met the eligibility criteria and were of sufficient quality (see table two) were included in the meta-analysis. The following data were extracted: the number of participants, mean angle of error measured using TTDPM and/ or JPS methods and accompanying standard deviation values to include in the meta-analysis and the following comparisons were made:

For joint position sense data:

- · ACL injured leg versus contralateral leg control

- · ACL injured leg versus external control leg

- · Patients with a reconstructed ACL versus patients with a deficient ACL

For data on the threshold to detect passive motion:

- · ACL injured leg versus contralateral leg control

· ACL injured leg versus external control leg

Firstly, comparisons were made using a fixed effect model with an inverse variance method as the outcome measures for both JPS (error matching score) and TTDPM (angular displacement before perception of movement) were consistent between the included studies. However, after consideration of the variability and specifically the heterogeneity values within the JPS and TTDPM protocols, a random effect model with an inverse variance method was also used for comparisons. All data was analysed and presented as forest plots using Review Manager Software (version 5.1). Standard mean difference between groups measured the effect size. Heterogeneity between comparable trials was tested using the chi squared test (level of significance = $p < 0.10$). Heterogeneity was further tested using I^2 percentages to consider the impact potential heterogeneity would have on the meta-analysis.

The initial search strategy yielded 3076 articles, 2737 of which did not relate to the research question. Screening of the titles and abstracts of the remaining 339 articles revealed that 290 did not fully meet the inclusion criteria; the main exclusion factor was the use of techniques to measure proprioception other than TTDPM and/or JPS. A further 43 articles were excluded as they provided 'poor' quality data with a high risk of bias and/or had missing or inadequate outcome data. The main reasons for missing data were that median data were presented instead of mean data or measures of the variability of the data (standard deviation) were missing. This left six studies which were selected for inclusion in the meta-analysis. The PRISMA flow chart detailing the selection process is shown in figure one.

The selected studies compared the injured leg to the participant's un-injured leg as the control (Fischer-Rasmussen and Jensen, 2000, Fremerey et al., 2000, Ozenci et al., 2007, Mir et al., 2008 and Angoules et al., 2011) using a range of JPS procedures. Results of the fixed effect model indicated the injured leg had significantly poorer JPS than the uninjured leg. Specifically, all included studies compared the injured leg to the participant's un-injured leg (n=170) as the control and provided a pooled standard mean difference of mean angle of error of 0.52° (95% CI [0.41 to 0.63]; P<0.001; I^2 = 63%) indicating that the un-injured leg had a lower mean angle of error (better joint position sense) compared to the injured leg. Fischer-Rasmussen and Jensen (2000), Fremerey et al., (2000), Ozenci et al., (2007) and Angoules et al., (2011) also compared the injured legs (n=140) to an external control (n=104). Again, results of the fixed effect model pooled data revealed the control group had better joint position sense than ACL patients. Specifically, the pooled standard mean

difference of the mean angle of error was 0.35° (95% CI [0.14 to 0.55]; P= 0.001; $I^2 = 78\%$) indicating that the control group had better joint position sense than ACL patients. Three studies (Fischer-Rasmussen and Jensen, 2000, Ozenci *et al.*, 2007 and Angoules *et al.*, 2011) compared ACL reconstructed (n=116) and ACL deficient (not reconstructed) legs (n=100). The pooled standard mean difference of the mean angle error was -0.62° (95% CI [-0.76 to -0.48]; P<0.001; $I^2 = 42\%$) indicating that ACL reconstructed patients had better joint position sense.

Results of the random effects model revealed similar findings to the fixed effects model findings for both comparisons between ACL injured and uninjured legs (mean angle of error 0.54°; 95% CI [0.36 to 0.72]; P<0.00001; $I^2 = 63\%$) and ACL reconstructed to ACL deficient (mean angle of error -0.63°; 95% CI [-0.81 to -0.45]; P<0.00001; $I^2 = 42\%$). Again, this supports JPS differences between ACL patients and the uninjured knee and ACL reconstructed versus ACL deficient. However, the random effects model found no difference in JPS between ACL injured legs and external controls (mean angle of error 0.41°; 95% CI [-0.03 to 0.86]; P=0.07; $I^2 = 78\%$). Therefore, there is some uncertainty in the findings of the meta-analysis.
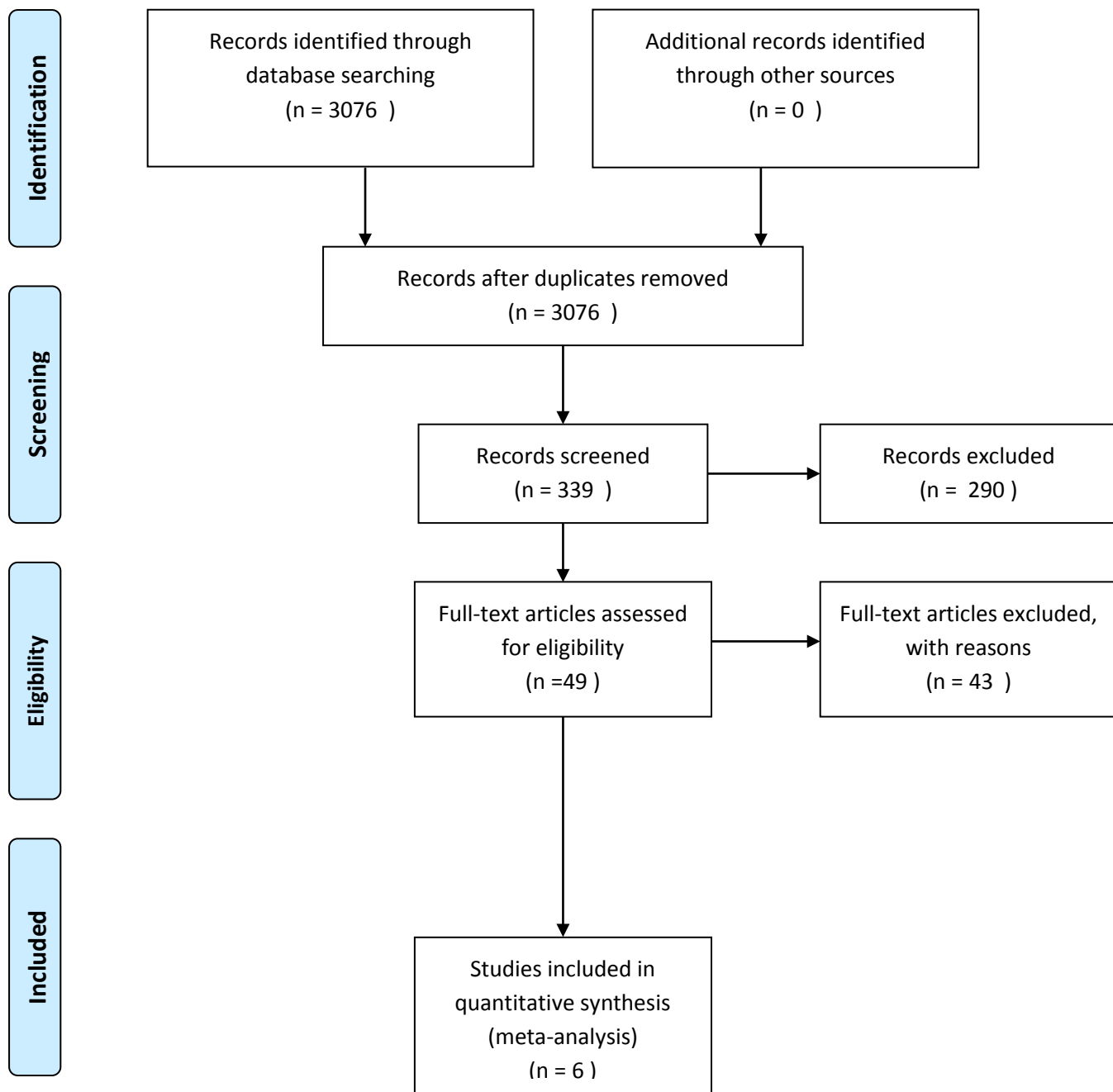
Figure 1: A PRISMA flow chart of article reduction.

A plethora of additional studies support the findings of the study by Relph *et al*., (2014). Some studies have used a visual analogue model instead of the contralateral or ipsilateral leg being used for replication of knee joint position to demonstrate JPS deficiencies in ACL injured patients (Bonfim *et al*., 2003, Roberts *et al*., 2000, Rehm *et al*., 1998, Barrett 1991a,

Carter *et al*., 1997). Poor JPS ability has also been evidenced using passive reproduction methods, in which participants deactivate knee movement using a switch on the apparatus when they feel they have reached the target position (Lee *et al*., 2009 and Zhou *et al*., 2008, Friden *et al*., 1997). Further evidence, using a passive followed by an active reproduction protocol in which participants use their own muscle force to replicate the target angle, provides more evidence of reduced JPS acuity following an ACL injury (Corrigan *et al*., 1992, Ochi *et al*., 1999, Katayama *et al*., 2004, Baumeister *et al*., 2008). Iwasa *et al*., (2000) measured JPS using a longitudinal research design and concluded it may take up to 18 months for complete restoration of JPS abilities. However, it should be noted that no pre-injury or normative data was available to make comparisons to post-operative levels. Also, Reider *et al*., (2003) reported significantly better JPS scores compared to external controls six months post-operative, suggesting rehabilitation may in fact improve JPS to levels above an uninjured population. Knee JPS was measured using passive-active methods discussed previously. Muaidi *et al*., (2009) considered knee JPS in the transverse place and presented similar results to previous sagittal plane studies, JPS was significantly reduced in ACL injured participants.

Ochi *et al*., (1999) explained JPS deficits using sensory evoked potentials, their results suggested reconstruction of the ACL preserved mechanoreceptors in the ACL and hence improved JPS compared to ACLs not reconstructed. Baumeister *et al*., (2008) measured electroencephalography (EEG) signals to consider varied cortical activity during JPS tasks in ACL injured participants. Results indicated ACL participants increased the cortical activity during tasks, this suggests they have higher attention to the task and hence may perceive the task as more complex than uninjured controls. Therefore ACL injured patients may have altered cortical activity and may find motor tasks more complex than pre-injury.

However, there is also significant evidence to suggest no JPS deficiencies exist following ACL injury when using passive-passive reproduction (Nishiwaki *et al*., 2007) passive-active reproduction (Remedios *et al*., 1998, Good *et al*, 1990, Harter *et al*., 1992, Dvir *et al.,* 1988, Fischer-Rasmussen *et* al., 2001, Jensen *et al*., 2002, Co *et al*., 1993, Friden *et al*., 1996, Friden *et al*., 1997, Fonseca *et al*., 2005, Roberts *et al*., 1999) active-active reproduction (Hopper *et al*., 2003, Dvir *et al*., 1988) and visual analogue reproduction (Roberts *et al*., 1999 and Friden *et al*., 1997). All of these studies concluded there is no difference between ACL injured and control groups and thus suggests an ACL injury has no negative effects on knee proprioceptive ability. It is possible other mechanoreceptors around the joint

compensate for the loss of ACL afferent signals. However, it may also be possible the methods used to measure proprioception did not involve ACL afferent input and hence deficits were not found.

Furthermore, potential sources of bias must be noted in all studies considering ACL injury and proprioception, regardless of their conclusions. Studies had to be excluded from the meta-analysis (Relph *et al*., 2014) data due to potential threats to reliability and validity. The majority of studies on this topic do not complete reliability and validity statistics of the measurement tool and therefore it is unclear if the data were viable. There are also issues with missing data in some studies; for example Friden *et al*., (1997), Roberts *et al*., (1999), Reider *et al*., (2003) and Friden *et al*., (1996) report median data instead of mean data therefore making comparisons to other findings difficult.

Therefore, the suggestion that ACL injuries negatively impact JPS appears intuitive, however the evidence is not as compelling as one might expect. For example within a single study, JPS ability is reduced in some measures, and not in others (Jensen *et al*., 2005 and Reider *et al*., 2003). The inconsistency in procedures between studies makes it very difficult to strongly conclude ACL injury does in fact reduce JPS ability. There are two theories to explain the discrepancy in results. Firstly, that the ACL does not play an important role in knee JPS, rather it is the knee musculature around the joint that is the dominant source of afferent information (Beard and Refshauge 2000). Secondly, that the measurement techniques employed are too variable, unreliable and inconsistent. As there is no standardised, reliable measure of JPS, authors have used a vast range of techniques, the majority of which are not tested for reliability and validity. Indeed, lack of reliability and validity measures in many studies led them to be excluded from the meta-analysis (Relph *et al*., 2014). For full details of articles not included in the meta-analysis (Relph *et al*., 2014) and evidence of the range of protocols used, please see appendix 1c.

The meta-analysis also considered the effect of ACL injury on dynamic proprioception measured using the threshold to detect passive movement (TTDPM). Relph *et al*., (2014) revealed two studies considering TTDPM of sufficient quality to be considered for inclusion in the meta-analysis (Barrack *et al*., 1989 and Ozenci *et al*., 2007). Both studies compared the injured leg (n=71) with the uninjured leg (n=71) in ACL patients. The pooled standard mean difference of mean angle error was 0.02° (95% CI -0.32 to 0.35; P= 0.91; $I^2 = 61\%$) indicating no difference. Barrack *et al*., (1989) and Ozenci *et al*., (2007) also compared ACL

injured legs (n=71) to external control legs (n=30). Results of the fixed effect model indicated a difference in mean angle error of 0.38° (95% CI 0.04 to 0.72; P= 0.03; $I^2 = 73\%$) indicating that the external control group had a better TTDPM than the injured leg group. The random effect model results provided opposite findings to the fixed effects model; ACL injured legs were significantly different to ACL uninjured leg (mean angle of error 0.39°; 95% CI [0.24 to 0.54]; P<0.00001; $I^2 = 50\%$) but not significantly different to the external control group (angle of error 0.45°; 95% CI [-0.21 to 1.11]; P=0.19; $I^2 = 73\%$). Therefore, as with the JPS meta-analysis findings, results are appear to be inconclusive.

There are additional studies that support the findings of the meta-analysis by Relph *et al*., (2014); however, potential risks of bias may be present. Studies excluded from the meta-analysis had missing data and did not appropriately present reliability and validity statistics on the chosen TTDPM protocols. Therefore these studies are considered here, but with caution. Many studies conclude TTDPM is significantly increased following ACL injury (Lephart *et al*., 1992, MacDonald *et al*., 1996, Courtney and Rine, 2006, Friden *et al*., 1999, Beynnon *et al*., 1999, Borsa *et al*., 1997, Corrigan *et al*., 1992, Reider *et al*., 2003, Lee *et al*., 2009, Roberts *et al*., 1999). In contrast, Valeriani *et al*., (1996) suggest ACL reconstruction does not restore TTDPM ability, measured using sensory evoked potentials. However, research by Pap *et al*., (1999), Foonseca *et al*., (2005), Nishiwaki *et al*., (2007), Jensen *et al*., (2002), Fischer-Rasmussen *et al*., (2001), Risberg *et al*., (1997) and Wright *et al*., (1995) conclude TTDPM ability does not reduce following ACL injury. It is difficult therefore to make clear conclusions regarding the effect of ACL injury on TTDPM. It may be TTDPM protocols are less sensitive than JPS to changes in knee proprioception following an ACL injury. Indeed the nature of the protocol, in which the knee is moved dynamically and then the patient responds, may not be sensitive enough to measure ligament deficiencies contributing to proprioception.

Furthermore the potential risk of bias in TTDPM studies is evident from the range of protocols used. As with JPS studies, there has been no standardised TTDPM measurement technique established, hence authors use which ever protocol they feel is most appropriate and often do not provide reliability and validity statistics related to their chosen protocol. This may explain why a number of authors found significant reductions in some TTDPM measures but not others (Friden *et al*., 1996, Friden *et al*., 1997 and Roberts *et* al., 2000, Co *et al*., 1993). See appendix 1c for more details of the excluded studies in the meta-analysis by Relph *et al*., (2014).

2.1.3 Summary

Results of the fixed effect meta-analysis (Relph *et al.*, 2014) indicated there are statistically significant differences in the proprioception, in terms of JPS acuity and threshold to detection of movement, of patients with ACL injury in that they have poorer proprioception than people without such injuries and poorer proprioception in the injured than uninjured leg. The proprioception of people whose ACL was reconstructed was statistically significantly better than those whose ligament is left unreconstructed (ACL deficient). These differences are seen whether the comparator group is a patient's uninjured leg, or a control group of people with no injuries; suggesting that either can be used as a control group in future research.

However, results of an additional random effect analysis revealed ACL patients may have worse JPS than their contra-lateral leg, but not compared to an external control group. Therefore, results are inconsistent and no clear conclusions can be made regarding ACL injury and proprioception. This is probably due to the large variation in approaches to JPS measurement, indicated in the analysis by the high I^2 scores (these ranged from 42% to 78%). Therefore, a consistent knee proprioception measurement protocol must be developed in order to distinguish whether ACL injury does indeed decline proprioceptive ability.

However, the significant differences that were reported in the meta-analysis were seen most clearly when joint position sense was measured but were less apparent when threshold to detect passive motion measurement techniques were used; the meta-analysis revealed greater differences in joint position sense (JPS) than studies using TTDPM. Furthermore, comparison of the fixed and random effects model results produced opposite findings, again suggesting the result of an ACL injury on dynamic proprioception is not clear. Techniques may be insufficiently sensitive to detect the responses of rapid receptors such as the pacinian corpuscles in the ACL (Barrack and Munn, 2000) as measurements incorporate the participants' reaction time, which is unrelated to their injury. JPS methods may be more sensitive as these measurements also incorporate the slower responses of the ruffini nerve endings and Golgi tendon organs (Schultz *et al.*, 1984) and allow the conscious perception of joint motion and position. Therefore, joint position sense should be used to measure knee proprioception.

These findings were supported by the majority of literature excluded from the meta-analysis (Relph *et* al., 2014). As stated previously, it is thought mechanoreceptors in the ACL provide

afferent information on the relative position and movement of the knee joint (Riemann and Lephart 2002a, Johansson *et al*., 2000, Schultz *et al*., 1984). Therefore, ACL injury may well impair proprioception through disruption to the transmission of this sensory information (Barrack and Munn, 2000). Marks *et al*., (2007) suggest other articular structures in the knee joint may attempt to compensate for the loss of ACL afferent signals. However, these compensatory signals may be '*nonphysiologically disorganised*' (Marks *et al*., 2007 p.42), and hence the central nervous system and consequently joint position are disturbed and the knee become more unstable. The differences in directional (i.e. flexion or extension) proprioception may be due to the location of the injury. The anteromedial bundles of the ACL are most taut in flexion, the posterolateral bundle tautest in extension. Therefore the area of deficiency may determine which direction the deficits in proprioception lie.

However, there is significant research to suggest injury may not reduce proprioceptive ability. In a similar study design to Relph *et al*., (2014), Fyhr *et al*., (2014) reported results of their meta-analysis on shoulder injuries and proprioception; it was suggested there is only limited to moderate evidence for a proprioceptive deficit following injury. Ambiguity in previous research can be attributed to differences in methods, for example research design, participant injury type, rehabilitation completed, equipment used, proprioception methods and outcome measures. Furthermore, very few studies on ACL injury and knee proprioception include information on the reliability, sensitivity and measurement error of the measurement techniques used. Generally the statistical analysis does not provide appropriate detail. For example only two studies in the meta-analysis (Mir *et al*., 2008, Angoules *et al*., 2011) reported whether the data was normally distributed and hence justified the use of parametric statistics. Many studies used 'home-made' measurement devices prepared specifically for data collection but the reliability and sensitivity were infrequently reported. Again, only two of the studies included in the meta-analysis reported reliability statistics. Mir *et al*., (2008) stated test-retest reliability using a correlation coefficient (0.99); however this was from a previous study which was not referenced. Angoules *et al*., (2011) did comprehensively report the accuracy of their data collection methods, reporting the standard error of measurement (SEM), coefficient of variation (CV), smallest detectable differences (SDD) and intraclass correlation coefficients (ICCs) for each of their seven measures of knee proprioception. Hence, as reliability and validity is lacking in the majority of studies it is possible that the differences in proprioception found after an

ACL injury are due to measurement error and/or the measurement techniques were insufficiently sensitive to detect clinically significant differences (Relph *et al*., 2014).

Another explanation is that the comparisons included in the meta-analysis could be under-powered because the sample was too small, (again, very few of the studies discussed calculated sample size using power estimations). However the pooled data from the meta-analysis (Relph *et al*., 2014) involved nearly 200 patients and the 95% confidence intervals of the comparisons made were small, indicating that a lack of power was not an issue. Further research is needed to evaluate the sensitivity and reliability of techniques to measure proprioception at the knee, before they can meaningfully be used as an evaluation tool.

A more likely, but controversial, explanation of such ambiguous findings is that ACL injuries do not have a major impact on proprioception at the knee. This might support the view that muscle, rather than ligaments, provide the primary afferent information in the sensorimotor system (Beard and Refshauge 2000) which is not a surprise given that only 1-2.5% of the ACL total area is made up of proprioceptive receptors (Barrack and Munn, 2000) and that receptors are often still deficient six months after reconstructive surgery (Barrack and Munn, 2000). It may, to some degree, also explain the inconclusive evidence for reconstructive surgery and conservative (non-surgical) rehabilitation (Beard and Refshauge 2000, Friden *et al*., 2001, Tagesson *et al*., 2008), while some patients 'cope' with an ACL-deficiency and have an apparently stable knee even after complete rupture, others do not 'cope' despite reconstructive surgery and apparent passive stability (Barrack and Munn, 2000, Beard and Refshauge, 2000, Herrington and Fowler, 2006, Friden *et al*., 2001). Given that joint stability relies on synergy between muscles and ligaments (Ryder *et al*., 1997, Lephart *et al*., 2000, Huston *et al*., 2000, Smith *et al*., 2010), once the ligament is damaged, patients may adapt by using proprioceptive information from the muscles to a greater extent to compensate for the lack of information from the ligament. This may explain why some patients cope better with ACL injury (however it is managed) than others (Herrington and Fowler, 2006); some may be more able to make that adaption more than others. The surgical treatment used to reconstruct the ACL may also influence proprioceptive rehabilitation. Although evidence shows auto-graft techniques can produce structural improvements such as stiffness and ultimate load that exceed uninjured ACLs (Woo *et al*., 2005), it is unclear whether the tissues used in this surgery allow mechanoreceptor regeneration or optimisation of the remaining mechanoreceptors. Therefore, surgical techniques may also hinder proprioceptive ability.

A limitation of research into ACL injury and proprioception is that all data collection is retrospective, which inevitably means pre-injury proprioception is unknown. It is possible that patients who suffered injuries had poorer proprioception which predisposed them to injury. Large scale normative studies are needed to give insight into the distribution of proprioception abilities across the population and whether this predisposes people to ACL injury. Such studies should consider a measurement technique that explores the full range of knee motion and direction using large sample sizes that represent the complete ACL patient population and normative data on proprioception ability.

It must also be noted that heterogeneity of variance in the referenced meta-analysis (Relph *et al*., 2104) and the fixed effect model was greater than the recommended level of 50% (Deeks *et al*., 2008) in all but one comparison; this may be due to variability in the recruitment strategies across studies. The time since injury when proprioception was measured and the use of rehabilitation programmes was not consistent. Highly varied measurement techniques were also evident, which is a limitation that hampers further analysis. Different pieces of measuring equipment and varied knee movements, in terms of direction and speed of motion, were employed (see appendix 1c). Proprioception increases towards the extremes of range of movement in order to protect the joint from injury (Barrack and Munn, 2000, Borsa *et al*., 1997), thus studies that do not include measurements across the whole range of movement may either be under- or over- estimating knee proprioception. These inconsistent methods of measuring proprioception could have contributed to the high levels of heterogeneity in the current analysis. However as there is no gold standard method of measuring knee proprioception, this variation was unavoidable.

This section of the thesis examined the effect of an ACL injury on proprioception, in terms of joint position sense and threshold to detect passive motion. The results indicate that patients with ACL injury may have poorer proprioception than people without such injuries and poorer proprioception in the injured than uninjured leg. The proprioception of people whose ACL is reconstructed may be better than those whose ligament is left unreconstructed (ACL- deficient). This may be due to an increase in knee stability. These differences are seen whether the comparator group is a patient's uninjured leg, or a control group of people with no injuries; suggesting that either can be used as a control group in future research. However there is variability in proprioceptive measurement techniques and a lack of reliability and validity statistics. There is also inconsistency in findings when

a fixed effect model is compared to a random effects model, again providing evidence that a standardised protocol for collecting knee proprioception is needed. There is also a need for large scale normative data to make appropriate comparisons to injured populations, indeed Stillman (2002) concludes "*clearly there is a need for more normative data derived from reliable instrumentation...*" (p.559). The following sections consider the topics of proprioception, and the current measurement tools of this "*sixth sense*" (Berthoz, 2002).

2.2.1 The Sensorimotor System

The sensorimotor system encompasses the complex relationship between the neurosensory and neuromuscular systems (Lephart *et al*., 2000). The system incorporates all sensory information from the visual, vestibular and peripheral mechanoreceptors to facilitate joint homeostasis (Riemann and Lephart, 2002a) (see figure 2). Although vision and vestibular inputs are important to joint stability, the peripheral nervous system is of most interest to orthopaedic and musculoskeletal practitioners and hence will be the focus of this thesis. The peripheral nervous system involves the communication and management of peripheral afferent information provided by mechanoreceptors or "proprio-ceptors" (Sherrington, 1906a) located in muscle, tendons, articulations and cutaneous tissue (Lephart *et al*, 2000). This information is processed by the central nervous system to control muscle activation and joint stabilisation (Riemann and Lephart, 2002a). It is believed that proprioception is an important aspect of this process and provides information on muscle length, tendon tension, joint position, joint movement and deep vibration (Lundy-Ekman, 2013).
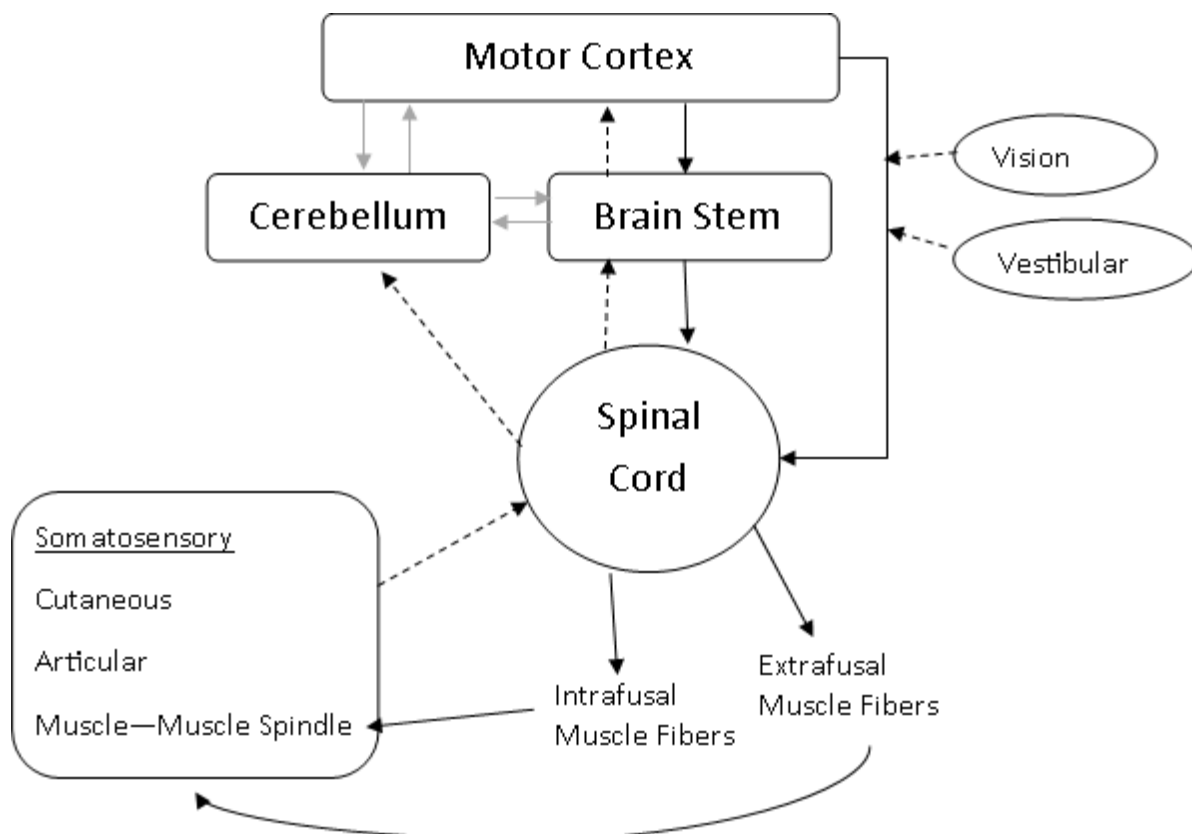
Figure 2. The sensorimotor system (adapted from Riemann and Lephart, 2002a, p.72). Dotted lines denote afferent pathways, solid lines efferent pathways and grey lines modification and regulation pathways.

In 1833 Sir Charles Bell referred to the ability to detect positions and actions of the hand as the "*sixth sense*" (McCloskey, 1978). Later the term "*kinaesthesia*" was coined by Bastian in 1888 and refers to the sense of position and movement of the joints (Proske and Gandevia, 2009). Following this the ground-breaking neurophysiologist Sherrington first published the term "*proprioception*" describing it as "*a deep field of receptors in which stimuli are traceable to actions of the organism*" (1906a, p. 472). The word itself is derived from the Latin for one's own (proprius) and receives (reception). It may be seen as a mysterious sense since we are largely unaware of it in our daily movements but yet it plays a crucial role in motor control (Proske and Gandevia, 2009). Sherrington's work forms the bases of current physiological understanding of the musculoskeletal senses (Stillman, 2002). He classified all senses and sense organs based on their source of stimulation, suggesting that each receptor type is activated by one accompanying type of stimulus (Sherrington, 1906a). There have been several interpretations of Sherrington's work and of the term "proprioception". Some authors regard proprioception as only the acquisition of senses from mechanoreceptors (Grigg, 1994), whilst others regard proprioception as the acquisition and processing of sensory information (Lephart *et al*., 2000). The term proprioception will be used in this thesis to describe the process of acquiring and processing sensory information from mechanoreceptors (specifically in the muscle, tendons, articulations and cutaneous tissue) to maintain joint stability and control muscle activation. Evidence has indicated both afferent and efferent information can determine position and movement of the limbs (Ogard, 2011, Gandevia *et al*., 2006). To note; the more global term of somatosensory sensations would encompass postural equilibrium, tactile, temperature and pain senses (Riemann and Lephart, 2002a) in addition to proprioception and as such will not be considered in detail in this thesis.

2.2.2 Peripheral Afferent (Sensory) Pathways

Mott and Sherrington (1895) were some of the first researchers to consider peripheral afferent information; their studies on primates indicated that surgical deafferentation of sensory endings in the upper and lower body caused extreme impairment and in some cases abolishment of movement. This strongly indicated afferent information is a key component in motor control. It is now known ascending nerve pathways forward sensory input from peripheral mechanoreceptors to the central nervous system for processing (Grigg, 1994, Mott and Sherrington, 1895). A mechanical stimulation, such as compression or deformation of a muscle or joint, causes a sensory response in mechanoreceptors. Pressure is transmitted to the sensory

nerve ending and changes the potential of this nerve ending (Lundy-Ekman, 2013). If this is of sufficient magnitude, a neural signal is propagated towards the central nervous system along ascending pathways. These pathways include the dorsal root ganglion to the spinal cord, to the brain stem and/or the cerebellum and basal ganglia, then from the brain stem to the motor/cerebral cortex (Lephart *et al*., 1998). A description of each type of peripheral mechanoreceptor is detailed below (also see table three). It is important to note that mechanoreceptors do not work independently of each other, indeed Sherrington himself referred to them as "allies" (Sherrington, 1906b). This concept will be explored later in this section of the thesis.

Table 3. Receptor name, classification, axon type, location and adequate stimuli (adapted from Richards and Selfe (2012) and Lundy Ekman (2013)).

Receptor name	Classification	Axon Type	Location	Stimulus
Muscle spindle	Ia	Large myelinated	Throughout muscle	Muscle stretch
Muscle spindle	II	Medium myelinated	Throughout muscle	Muscle stretch
Golgi tendon organ	Ib	Large myelinated	Musculotendinous junction	Strain/ Tension
Pacinian corpuscle	II	Medium myelinated	Capsule, ligament, menisci, fat pads, skin	Compression
Ruffini ending	II	Medium myelinated	Capsule, ligament, menisci, skin	Stretch, strain
Free nerve ending	Aδ	Small myelinated	Capsule, ligament, menisci, skin	Nociceptive
Free nerve ending	C	Small unmyelinated	Capsule, ligament, menisci, skin	Nociceptive
Meissner's corpuscles	Aβ	Medium myelinated	Skin	Deformation caused by light touch.
Merkel's discs	Aβ	Medium myelinated	Skin	Continuous pressure

Muscle-Tendon Unit Mechanoreceptors

Muscle Spindles

The number of muscle spindles serving each limb joint significantly declines from proximal to distal positioning, for example there is an estimated 1821 muscle spindles serving the knee joint compared to the 6659 approximate muscle spindles assisting the cervical spine (Scott and Loeb, 1994). Muscle spindles provide important sensory information regarding muscle tension or length of muscle fibres and the velocity of change of muscle displacement (Collins *et al*., 1998, Edin and Johansson, 1995, Gandevia *et al*., 1992b, Matthews and Stein, 1969). The muscle bellies contain intrafusal fibres, which are made up of nuclear bag and nuclear chain fibres (Lundy-Ekman, 2013).

Nuclear bag fibres respond directly to quick and sustained spindle stretch (Type Ia), and the frequency of firing increases as stretch increases (Proske *et al*., 2000). A second smaller group of sensory fibres (annulospiral endings, Type II) attach mainly to the nuclear chain fibres and respond with lower frequencies to sustained stretch (Proske *et al*., 2000, Matthews, 1987). The currently accepted view is that primary endings (Type Ia) of spindles contribute to sense of position and movement, whereas secondary endings (Type II) respond to position sense alone (Proske, 2006). For most types of receptors in the body an increase in discharge rate corresponds to an increase in stimulus intensity; however an increase in muscle spindle discharge rate represents a longer muscle not an increase in stimulus (Proske, 2006). This is because muscle spindle discharge rates increase in approximate proportion to the size of the lengthening (Proske, 2005). Furthermore, all muscle spindles are recruited at just 25% of maximum contraction, making them very sensitive to the stimulus (Proske, 2006) which is again different to other types of receptors.

Further, the spindles in most muscles do not span the entire length of the fascicle to prevent the intrafusal fibres from becoming too compliant (Proske *et al*., 2000, Proske and Gandevia, 2009). The ends of intrafusal fibres are attached to extrafusal fibres (Lundy-Ekman, 2013) and such work together in sensory feedback. Evidence also suggests coupled muscles, such as agonist, antagonists and synergists, provide a heightened proprioceptive ability when working together (Ribot-Ciscar and Roll, 1998), hence both muscle groups provide simultaneous afferent information (Grigg, 1994). In addition, the afferent signals transmitted from one muscle alone do not provide sufficient information for successful proprioceptive ability (Ribot-

Ciscar *et al*., 2003). Therefore it follows that proprioception would be at an optimum when all involved musculature of a movement contribute to the afferent signal.

There is also strong evidence that suggests muscle contraction during active movement increases muscle spindle activity in contrast to passive movement (Gandevia *et al*., 1992b). The type of muscle contraction will also influence spindle afferent discharge, for example when muscle spindles fire there is an increased afferent signal during lengthening of a muscle compared to shortening of that muscle (Ribot-Ciscar and Roll, 1998, Matthews, 1987). This suggests that as joints move through a range of motion, the predominant source of muscle spindle afferent information changes, the signals increase towards the lengthened muscle. However, this could also imply that "net" muscle spindle activity across all involved muscles stays constant simply switching between agonist and antagonist depending on the direction of movement. This theory has yet to be confirmed by experimental data.

Golgi tendon Organs in muscle

Golgi tendon organs are situated within muscle bellies near musculotendinous junctions or within tendons and provide additional extrafusal fibres (Type Ib) (Jami, 1992, Stillman, 2000). These mechanoreceptors average length and diameter is 1600µm and 122µm respectively (Jami, 1992). Golgi tendon organs detect differences in tension and force (Proske *et al*., 2000) but not length (Riemann and Lephart, 2002a), dynamically responding to rapid increases in these two stimuli only. Therefore, due to the high threshold and brief response, it is thought Golgi tendon organs have a protective mechanism near a joint's extreme range of motion when tension rapidly increases (Johansson *et al*., 2000). However, previous literature has illustrated Golgi tendon organs may not fire during passive movement (Riemann and Lephart, 2002a) and hence are thought of as purely active mechanoreceptors.

As stated, Golgi tendon organs are predominately tension or force receptors therefore it may be the amount of load or muscular contraction occurring during passive movement is below the threshold potential of the respective mechanoreceptor (Bergenheim *et al*., 1996, Jami, 1992). Indeed research demonstrates Golgi tendon organs have much higher activation thresholds for passive force than for active force (Stuart *et al*., 1972; Stuart *et al*., 1970). There is also error in joint proprioception ability when isometric contractions occur (Grigg, 1994). It is thought that Golgi tendon organs provide force-related information, when this is added to muscle spindle length information during isotonic contraction the combination of afferent signals produces accurate proprioception. However, during isometric contractions the force

and muscle length afferent information is conflicting, it appears large forces are not accompanied by displacement of the joint. Therefore this may confuse the CNS and reduce proprioceptive ability (Rymer and D'Almeida, 1980, Gandevia *et al*., 2006). This provides evidence for an important role for both muscle and tendon mechanoreceptors in proprioception during movement.

Articular Mechanoreceptors

Golgi-like Tendon Organs

In contrast to Golgi-tendon organs situated near musculotendinous junction, Golgi tendon organs located in joints provide afferent information on joint angle or position and not force or tension (Solomonow and Krogsgaard, 2001). It is suggested these types of Golgi tendon organs that are found in the knee joint provide constant levels of afferent information throughout the voluntary range of motion (Rymer and D'Almeida, 1980).

Pacinian Corpuscles

Pacinian corpuscles are small ellipsoidal nerve fibres situated close to Golgi-like tendon organs with axon diameters between 8 and 12µm (Lundy-Ekman 2013). They have a low threshold and rapidly adapt to phasic movements earning them the exclusive classification of "dynamic receptors" (Riemann and Lephart, 2002a). Previous literature has shown pacinian corpuscles rapidly sense acceleration and deceleration and hence changes in movement, but not static or constant joint rotations (Johansson *et al*., 2000). Therefore they detect the onset or termination of movement, but not constant joint displacement.

Ruffini Endings

Ruffini endings are found in the collagen aspects of fibrous capsules, primarily in the flexion side of the articulation, hence the side that is stretched during extension (Grigg, 1994). Ruffini endings typically have diameters between 5 and 9 µm and are both static and dynamic receptors as they have a low threshold but slow adapting characteristics (Riemann and Lephart, 2002a). They are found in articulations and cutaneous areas and hence provide sensory feedback on joint and skin tension applied in all directions and information on joint position, movements and also pressure (Stillman, 2000, Grigg, 1994). Due to their slow adapting characteristics it is believed Ruffini endings contribute to joint position sense (Burke *et al*., 1988). These receptors

are most sensitive at maximum flexion and extension positions (McCloskey, 1978, Burgess *et al.*, 1982).

Free Nerve Endings

The majority of free nerve endings are unresponsive during normal joint movement, however, are active when damage or injury occurs in the articular tissue (Johansson *et al.*, 2000). Therefore, research suggests this receptor provides afferent information only once the joint is damaged via nociceptive sensory input (Solomonow and Krogsgaard, 2001, Hogervorst and Brand, 1998).

Cutaneous Mechanoreceptors

Meissner's corpuscles and Merkel's discs

Meissner's corpuscles are responsive to light touch and vibrations. Merkel's discs are stimulated by skin pressure and hence contribute to proprioception when the skin is stretched (Burgess *et al.*, 1982). Although neither of these receptors is thought of as a true "proprioceptor" the afferents they provide have a minor role in joint position sense and kinaesthesia (Edin and Johansson, 1995, Grigg, 1994, Matthews, 1987, McCloskey, 1978). It is intuitive that the sense of skin movement through stretch or pressure may contribute to our overall proprioception ability, although the presence of Ruffini corpuscles in the skin may also contribute specifically to joint position sense (Edin and Johansson, 1995). However, there is little evidence to fully support this theory. Grigg (1994) suggests this is due to the difficulties in isolating cutaneous receptors and hence measuring specific cutaneous responses to joint movement. Although this can also be disputed using evidence that the afferent signals provided by cutaneous receptors are time and speed dependent; after 1-2 minutes and at speeds under 0.1mm/s cutaneous sensation ceases (Horch *et al.*, 1975, McCloskey, 1978). Cutaneous receptors may therefore be thought of as secondary or facilitating contributors to proprioception (Burgess *et al.*, 1982).

2.2.3 Summary

Although it is believed sensory information from all receptors may be integrated at the spinal level, there has been debate over which receptors are most prominent in proprioception processing (Proske *et al.*, 2000). In the 1950s authors believed articular receptors may be the most prevalent in proprioception due to lack of evidence at that time that Type 1 (muscle

spindle) afferent information was ascended to the cerebral cortex (Riemann and Lephart 2002a, Matthews, 1987, Proske, 2005). Also, authors at this time believed it to be more logical to look for dominant joint movement receptors within the joints themselves. However, latterly authors have reverted back to the traditional belief of Sherrington's (1906b) "*muscular sense*", that is the most dominant mechanoreceptor in proprioception to be muscle spindles (Scott and Loeb, 1994, Proske and Gandevia, 2009, Proske *et al*., 2000, Proske *et al*., 2005, McCloskey, 1978). Indeed feline studies have indicated the knee joint is served by 400 myelinated joint afferents but 4000 myelinated muscle afferents. This principle is supported by evidence suggesting articular receptors may not be as responsive in mid-range movements (Rymer and D'Almeida, 1980, Burke *et al*., 1988, McCloskey, 1978) and hence cannot be the most important proprioceptor. Furthermore, studies have illustrated joint proprioception is not lost when articular and cutaneous afferent information is blocked (Clark *et al*., 1979). Vibration and tendon pulling studies have suggested muscle receptors must have the dominant role in afferent signals as an illusion of joint movement can be induced with these techniques (Matthews, 1987, Proske and Gandevia, 2009, Berkinblit *et al*., 1992). For example Goodwin *et al*., (1972) published ground-breaking evidence that when a muscle belly is vibrated the participant experiences illusions of movement and position changes, however if this vibration is moved to the joint, no illusion occurs. Thus it is now more popular to believe muscle spindles may be the main afferent provider for proprioceptive processes.

However receiving only muscle afferent information does actually significantly reduce proprioceptive ability (Grigg, 1994), hence it is most likely that all mechanoreceptors contribute to effective proprioceptive ability in some way (Gandevia and Burke, 1992a, Millar, 1973, Proske *et al*., 2000). Grigg (1994) proposed that as the joint moves closer to its end range of motion, the change in muscle length is reducing and hence muscle afferent information is reducing; however concurrently the change is joint tension is increasing and hence articulation mechanoreceptor information is increasing. Therefore, it may be that the primary mechanoreceptor changes across the range of motion (Burgess *et al*., 1982). This is supported by the "ensemble coding theory"; this theory suggests afferent information is transmitted by different populations (ensembles) of receptor afferents. The ensemble must constitute receptors with a range of sensitivity and hence show different responses to stimulus to provide the most useful afferent signal (Bergenheim *et al*., 1996, Jones, 1993). It is believed this range of responses affords the ensemble to encode a greater amount of stimuli and provide the most

useful and a manageable amount of afferent information to the central nervous system (Bergenheim *et al*., 1996).

Following stimulation of mechanoreceptors, afferent information is sent, in the first instance, to the spinal cord (Lephart *et al*., 1998). Proprioceptive information is relayed to the higher central nervous system via the two dorsal lateral tracts and the spinocerebellar tracts (Lundy Ekman 2013). The two dorsal tracts are located in the posterior region of the spinal cord and transport conscious proprioceptive information such as position and kinaesthetic sensations (Bosco and Poppele, 2001). The spinocerebellar tracts are believed to be responsible for relaying unconscious proprioception, such as joint angles, muscle tension and length (Dye, 2000, Bosco and Poppele, 2001). This information is vital in reflexive, automatic and voluntary muscle contractions. This pathway is also involved in the transmission of an efference copy of all motor information back to the cerebral cortex (Dye, 2000); this will be discussed in a later section on the cerebellum. The following section details the continued pathways at the central nervous system and descent pathways to muscle spindles.

2.2.4 Central Efferent Pathways

The central efferent pathways are responsible for the processing of afferent proprioceptive information ascending from the peripheral nervous system (Riemann and Lephart 2002b). There are two divisions; automatic (involuntary) and somatic (voluntary) nervous system and within these divisions two mechanisms; feedback and feedforward motor responses (Biedert, 2000). The motor components that comprise the efferent pathways can be divided into the central axis and two associated areas (Lundy Ekman, 2013). The central axis contains the spinal cord, brain stem and cerebral cortex (three levels of motor control). Motor output at these three levels are proceeded by afferent input, the response can be reflexive (spinal cord) or descending motor commands from the brain stem and/or cerebral cortex (Lephart *et al*., 1998). The associated areas are the cerebellum and the basal ganglia; these being responsible for modulation and regulation of motor commands (Biedert, 2000). Motor commands can both inhibit and facilitate sensory relay to peripherals. The following section will detail the three levels of motor control and the associated areas.

The Spinal Cord

The spinal cord contains three types of neuron: motor neurons, sensory neurons and interneurons (Bosco and Poppele, 2001). The motor neurons run through the ventral horn to

supply muscle fibres. Sensory nerve fibres enter the spinal cord via the dorsal horn (Stillman, 2000). The spinal cords main contribution to integration of afferent information is to provide the space in cord grey matter for synapses to occur between mechanoreceptor transmission and interneurons (Barrack *et al*., 1994). This sensory information may be transmitted to other interneurons, higher motor centres and other antagonistic motor neurones (Bosco and Poppele, 2001). The spinal cord is also responsible for the quickest response to peripheral afferent signals, the reflex response (Hewett *et al*., 2002). This response is necessary for protective reflexes in joint stability (Hewett *et al*., 2002).

Brain Stem

The brain stem had a significant role in postural equilibrium and autonomous movement through integration of visual, vestibular and all somatosensory sources (Lephart *et al*., 1998). It is under direct cerebral cortex command and provides the relay between the spinal cord and the cortex (Lundy-Ekman, 2013). Specifically, the medial neural pathway from the brain stem descending to the spinal cord influences axial and proximal muscles, whilst the lateral neural pathway controls distal muscles. Evidence also states the brain stem contributes to spinal reflexes and muscular tone (Lundy-Ekman, 2013).

Cerebral Cortex

The cerebral cortex is the highest level of motor control and is responsible for complex and discrete voluntary movements (Lephart *et al*., 1998). Efferent signals are transmitted from the cortex both directly to the spinal cord into interneurons and motor neurones or indirectly via the brain stem (Barrack *et al*., 1994). The major neural pathway from the cortex to the spinal cord is the corticospinal tract (Riemann and Lephart 2002a). Riemann and Lephart (2002a) describe three main areas of somatosensory management. The primary motor cortex is most directly responsible for muscle contraction, using information from several afferent pathways to determine the muscles that are activated, the muscular force of the movement and the direction of movement (Riemann and Lephart 2002a). The pre-motor area, as the name suggests, is indirectly responsible for muscular contraction, organising and preparing the motor commands and the supplemental area assists the primary motor area when programming complex, muscles group contractions (Riemann and Lephart, 2002a). The supplementary area works with the pre-motor area to control bi-lateral synergic movement (Lephart *et al*., 2000).

Cerebellum

The cerebellum has a vital role in the correct sequencing of motor activity. This part of the brain "*contains more nerve cells than the rest of the central nervous system combined*" (Dye, 2000, p31) and as such may be expected to have this critical role. It is believed the cerebellum is responsible for feedback, feedforward and error correction processes. Bhanpuri *et al.*, (2013) explains the cerebellum predicts body state (i.e. position, acceleration) from a copy of motor commands (known as an efference copy) plus previous knowledge on body movement. Hence perception of sensory information occurs in the cerebellum providing meaningful interpretation of sensory information (Lundy-Ekman, 2013, Proske and Gandevia, 2009). Afferent information is ascended to the cerebellum through the dorsal and ventral spinocerebellar tracts (Bosco and Poppele, 2001). The neural pathways along these tracts are the most rapidly conducting nerves in the entire neurological system reaching speeds of around 100m/s (Dye, 2000). The dorsal tracts provide information from the various mechanoreceptors (Bosco and Poppele, 2001). The ventral tract provides the efference copy of all neurological signals already sent to the spinal cord, and hence it is believed to monitor millions of motor unit contractions, for example agonist and antagonist muscle actions (Dye, 2000). This neurological copy is used to monitor and adjust motor activity; this is done by comparing the intended motor commands of the cerebral cortex to the actual musculoskeletal movement (Dye, 2000), for example during isometric contractions, in which receptors are stimulated, but no movement occurs (Rymer and D'Almeida, 1980).

The term "efference copy" was first proposed by Sperry (1950) and Von Holst and Mittelstaedt (1950). The CNS compares the efferent command with the expected afferent feedback; the reafference (Sperry, 1950). If the two signals match, i.e. if the efferent command minus the reafference equates to zero or a null point the motor act is perceived as successful. However any additional afferent feedback (known as exafference) from the external environment is reported to the sensory centres (the corollary discharge) and may be perceived as a sensation in its own right (Gandevia *et al.*, 2006). This process allows the CNS to account for afferent activity arising from the motor act itself and hence provide a meaningful signal from muscle spindles (Proske, 2005). However, it is important to state there is no direct supporting evidence for a central subtraction process at this time (Proske, 2006).

The feedforward motor commands are not fully understood, but it is believed they play a vital role in preparing the body for impending movement. The lateral zone of the cerebellum is thought to facilitate this planning - "*…neurones in the dentate nucleus manifest a copy of the next sequence of motor signals at a time when a current musculoskeletal movement is in*

progress..." (Dye, 2000 p. 33). This predictive ability reduces the dependence on peripheral feedback that is time-delayed (Bhanpuri *et al*., 2013). This theory is supported by work from Bhanpuri *et al*., (2013); this research group compared the performance of simple, complex and complex disturbed tasks between patients with cerebellum damage and healthy controls. Results implicated an important role for the cerebellum during active predictive tasks, the control group performed better than the patient group in this condition. However, if the task was disturbed and hence unpredictable, both groups performed poorly, the cerebellum was unable to provide useful feedforward and preparatory information. The exact role of the cerebellum is not yet fully understood (Boisgontier and Swinnen, 2014) however, it is clear that this component of the central nervous system plays a vital role in motor control and activity.

Basal Ganglia

The basal ganglion has a direct connection with the cerebral cortex only and it is believed this area of the brain is responsible for higher order aspects of motor control, receiving input from all areas of the cerebral cortex, not just sensorimotor information (Riemann and Lephart, 2002a). Research has yet to fully explain the role of the basal ganglia in body homeostasis (Lundy-Ekman, 2013).

2.2.5 Efferent Information in Muscular Contraction

Lower motor neurones responsible for muscular contraction are alpha and gamma motor neurones (Proske *et al*., 2000). Alpha (α) motor neurons have large diameters up to 20 μm and smaller efferent gamma (γ) motor neurones are no larger than 10 μm (Lundy-Ekman, 2013). Gamma motor neurones can be divided into gamma d (dynamic sensitivity) and gamma s (static sensitivity) (Riemann and Lephart 2002a). Gamma motor neurones connect with stretch receptors to detect minute changes in muscle fibre length (Stillman, 2000). Gamma motor neurones are constantly updated with sensory input from peripheral receptors in joints and also efferent information from the corticospinal tract (Stillman, 2002). Furthermore the activation of alpha motor neurones cause excitation of gamma motor neurones, hence an increase in sensitivity of muscle spindles to stretch, and increase awareness of proprioception and stretch reflexes (Palastanga and Soames, 2012).

The thin gamma efferent motor neurones innervate the contractile ends of the intrafusal fibres and serves motor function driven by the central nervous system (Palastanga and Soames, 2012).

Changes in gamma efferent activation enable the spindle to continuously monitor and regulate length of the muscle. The "gamma motor neurone loop" which consists of gamma motor neurones – muscle spindles – primary muscle spindles afferent pathways, contribute to muscle stiffness regulation (Biedert, 2000, Burgess *et al.*, 1982). It is further suggested that this process may pre-programme (feedforward) joint stiffness and muscle stiffness (Riemann and Lephart, 2002a).

2.2.6 Summary

Important afferent information arising from a range of muscle, tendon, articular and cutaneous mechanoreceptors is acquired, synthesised, and transported to all levels of the central nervous system. This information is uniquely processed at specific central nervous system levels and an appropriate response is conveyed to the necessary muscles. There is a complex relationship between afferent and efferent pathways and it is overly simplified to describe them as a simple input-output procedure (Kalaska, 1994). This specialised system is responsible for joint homeostasis during movements and its overall aim is to ensure optimised motor control of the body. The following section considers proprioception relative to the knee joint.

2.3.1 Knee proprioception

The knee is one of the most complex anatomical structures in the body (Dye and Vaupel, 2000, Lloyd *et al.*, 2005), managing high loads between the femur, tibia, fibula and patella. The surrounding muscles are the quadriceps and hamstring groups whose co-contraction helps stabilise flexion and extension of the joint. The articulation includes the femorotibial joint, patellofemoral joint and the joint capsule. Normal loading of the knee during walking ranges from 1.7BW to 4.3BW depending on the measurement tool (Komistek *et al.*, 2005). In the past, joint tissues such as ligaments have been thought of as solely passive structures contributing to mechanical joint stability only (Johansson *et al.*, 1991a). However, research now suggests tissues within the knee may contribute to sensory afferent information and hence active or functional joint stability and coordinated movement (Dye and Vaupel, 2000, Johansson et *al*, 1991a, Stillman, 2000). The majority of investigators have considered an important sensory role for knee joint ligaments and capsules, one of the first being Abbott *et al,* in 1944, and more recently, the Kennedy group in the 1980s and the Johansson group in the 1990s. It is believed knee joint capsules and ligaments provide conscious knee joint position sense and kinaesthesia to the central nervous system and may have a role in protective reflexes (Barrack *et al.*, 1994,

Zimny, 1988, Stillman, 2000). The following sections discuss each of the pertinent knee ligaments plus tissues in the joint capsule believed to have a sensory feedback role.

2.3.2 The Anterior Cruciate Ligament (ACL)

The ACL is the primary ligament restraint to anterior tibia draw (Dye and Vaupel *et al*., 2000) and secondary restraint to internal rotation (Duthon *et al*., 2006). The ligament originates on the lateral femoral condyle within the intercondyle notch and inserts into the middle section of the tibial plateau (Duthon *et al*., 2006). It is composed of the anteromedial and posterolateral bundles, both contributing to knee stability by resisting tension created during loading (Woo *et al*., 2005). The ACL can sustain 2000N before rupture in cadaver models; however hamstring quadriceps co-contraction prevents this level of loading in human movement (Krogsgaard *et al*., 2002). The anteromedial bundle is under more force during angles closer to 90° whereas the posterolateral bundle is most taut during full knee extension (Woo *et al*., 2005). In addition to mechanical properties, the ligament is also thought to provide important sensory information during knee motion.

Schultz (1984) was the first to discover mechanoreceptors (specifically Golgi-like tendon organs) in the ACL supplied by the posterior articular nerve (PAN). It is now suggested that between 1-2.5% of the ligament is made up of neural elements (Friden *et al*., 2001). Further histology research indicates the ACL contains ruffini nerve endings, Golgi-like tendon organs and pacinian corpuscles (Hogervorst and Brand, 1998, Jennings, 1994, Duthon *et al*., 2006, Schutte *et al*., 1987, Adachi *et al*., 2002, Stillman, 2000). Connections have been established between these mechanoreceptors and the central nervous system, specifically the spinal dorsal ganglion (Madey, *et al*., 1993) and the cerebral cortex (Pitman *et al*., 1992). ACL mechanoreceptors can respond to relatively small tensile loads, between 5 to 40N (Johansson *et al*., 1991a).

The highest density of ACL mechanoreceptors is situated close to the tibial insertion of the ligament but receptors have also been located beneath the synovial membrane and the femoral insertion (Schultz *et al*., 1987). As discussed earlier, mechanoreceptors only become stimulated when the neurone excitation reaches a critical level, this can be related to particular joint positions. The ACL is most taut in extreme extension (Fuss *et al*., 1989) and hence more mechanoreceptors are stimulated in these positions. However, research has also evidenced certain fibres (specifically containing ruffini nerve endings) in the ACL can also be taut across

the whole range of motion, specifically to ensure that the distances between the origin and insertion of the cruciate ligaments remains constant and hence the articular surface between the femur and tibia is also constant (Johansson *et al.*, 1991a). Therefore, it is believed the ACL has the ability to provide sensory information throughout all ranges of movement (Johansson *et al.*, 1991a). Despite this theory, there is still a disproportionate amount of ligament receptors that fire during extreme extension compared to those during mid to low ranges of motion (Barrack *et al.*, 1994).

The ligament may also send important position sense information during internal and external rotation at extreme extension and hence communicate potential impending injury (Barrack *et al.*, 1994). Research has indicated afferent signals from the ACL may elicit a muscular reflex from the hamstrings that inhibits knee extension and facilitates knee flexion thus removing the knee from a position of injury risk (Marks *et al.*, 2007, Barrack *et al.*, 1994, Solomonow and Krogsgaard, 2001, Tsuda *et al.*, 2001). However, the latency of these reflexes may not be sufficient in protecting the joint from injury during high loading events (Pope *et al.*, 1979). However during normal loading events the ACL may indeed send afferent information which causes an increase in the gamma motor neurone activity and hence muscle spindle sensitivity (Shultz *et al.*, 2007, da Fonseca *et al.*, 2004). This will be discussed further in a later section.

2.3.3 The Posterior Cruciate Ligament (PCL)

The PCL is the primary restraint to posterior tibia draw, attached to the femoral intercondyle notch and posterior tibial "shelf" (Amis *et al.*, 2006). The ligament is made up of two bundles, the anterolateral and posteromedial bundles. The posteromedial bundle is tauter during knee extension, and hence mechanically resists hyper-extension and is also taut in hyper-flexion. The anterolateral bundle is most resistant in flexion (Amis *et al.*, 2006). In addition to passive resistance, the PCL is also thought to have a role in knee proprioception.

There are fewer studies into the role of the PCL in knee joint proprioception; perhaps due to the reduced number of injury occurrence in this ligament. However, a study by Katonis *et al.*, (1991) confirmed the presence of ruffini endings, pacinian corpuscles and free nerve endings in the PCL. As with the ACL, there appears to be higher densities of these mechanoreceptors near the attachment sites (Katonis *et al.*, 1991), hence it may be pertinent to assume during knee flexion, when both bundles of the PCL are taut, proprioception will be heightened. Del Valle *et al.*, (1998) considered PCL mechanoreceptors of patients undergoing surgery for total

knee arthroscopies with comparisons to controls (cadavers). Their results concur with Katonis *et al.*, (1991); both ruffini endings and pacinian corpuscles were found in the ligaments of both patient and control groups, but no Golgi-like tendon organs were present in either group. Interestingly, mechanoreceptors were also discovered in the arthritic knee joints, however although present, it is unclear if function would be the same as prior to injury (Mihalko *et al.*, 2011). There is also some evidence of a PCL-quadriceps reflex (Solomonow and Krogsgaard, 2001, Krogsgaard *et al.*, 2002); this reflex may inhibit muscle contraction and reduce knee extension force. However this has not been confirmed in the literature.

2.3.4 Additional Knee Joint Mechanoreceptors

The main focus of research to date has been on mechanoreceptors located in the ACL and PCL. However, there is some evidence that the medial collateral ligament (MCL) and lateral collateral ligament (LCL) contain Golgi-like tendon organs and ruffini endings (Solomonow and Krogsgaard 2001, Dyhre-Poulsen and Krogsgaard, 2000) but not pacinian corpuscles. This suggests the collateral ligaments would not provide afferent information on rapid acceleration or deceleration of the joint. De Avila et *al.*, (1989) conclude due to the scarcity of mechanoreceptors in the collateral ligaments, they may only be important in protecting injured joints, when other mechanoreceptors in the cruciate ligaments have been lost. However, there has also been some minor evidence of a MCL-sartorius/ quadriceps reflex (Kim *et al.*, 1995), although again this has not been well documented.

The menisci are crescent shaped areas, made up of fibrocartilage situated in the condyles of the femur and tibia (Marks *et al.*, 2007). The majority (up to 90%) of menisci is Type 1 collagen. However, mechanoreceptors including ruffini endings, pacinian corpuscles and Golgi-like tendon organs have been identified in the medial meniscus, particularly in the posterior horn (Friden *et al.*, 2001). There is also some evidence to suggest the medial meniscus is connected to the cerebral cortex (Pitman *et al.*, 1992).

Dye *et al.*, (1998) used conscious mapping of the internal structures of the knee joint without use of anaesthesia to isolate specific sensory contributions of intra-articular structures. Results indicated a level of sensory control for the majority of intra-articular aspects of the knee joint. Therefore knee joint tissues other than the cruciate ligaments may contribute some afferent information during knee movement.

2.3.5 Summary

Despite a wealth of research there are limitations to histological mechanoreceptor studies; the use of gold and silver chloride stains is not always accurate and vascular structures can be mistaken for mechanoreceptors (Johansson *et al*., 2000, McCloskey, 1978). The classification of mechanoreceptors is also inconsistent and the identification alone of mechanoreceptors does not imply functionality (Johansson *et al*., 2000, McCloskey, 1978). However, due to the vast amount of research on the knee joint, we can somewhat confidently conclude mechanoreceptors are present in articular and periarticular areas. Two main theories are proposed to explain the management of afferent information provided by articular mechanoreceptors. The first theory discusses H-reflexes including medial collateral, lateral collateral anterior cruciate and posterior cruciate ligament – muscular reflexes (Dyhre-Poulse and Krogsgaard, 2000). This hypothesis is not a current one, Hilton in 1863 stated "*muscles, indeed, appear to be told, through the medium of the nerves of the interior of the joint, that its articular structures are overtasked*" (p.169). Early direct studies were on feline animals using the cranial cruciate ligament a comparable ligament to the ACL (Cole *et al*., 1996). Results provided evidence of neural adaptations that would support a ligament-reflex response following stimulation of the ligament.

The most commonly researched is the ACL-hamstrings reflex (Krogsgaard *et al*., 2002). This theory states afferent information from the ligament creates excitation of the hamstring muscle fibres and hence acts as a protective mechanism (in this case to hyperextension) (Tsuda *et al*., 2001, Dyhre-Poulsen and Krogsgaard, 2000). The afferent signals from the ACL either activate or inhibit hamstring muscle spindles via the gamma motor neurone system (Dyhre-Poulse and Krogsgaard, 2000). This reflex has a latency of between 95-110ms (Dyhre-Poulse and Krogsgaard, 2000, Krogsgaard *et al*., 2002) and hence cannot be a protective mechanism. Pope *et al*., (1979) also discredited a protective reflex theory using basic calculations of time latencies following a theoretical ski injury. They concluded the ligamento-muscular reflex would take 89ms to activate whereas the ligament would fail at 34ms following knee loads. Therefore, the authors proposed an alternative function for knee joint afferent signals during joint stability.

A more feasible theory is the contribution to pre-programming of muscle stiffness around the knee joint (Johansson *et al*., 1991a, Johansson *et al*., 1991b). It is thought joint afferent signals feed in to gamma motor neurones in the muscle spindle. This information contributes to the "final common input", that is information from muscle spindles, joint mechanoreceptors and potentially other mechanoreceptors to regulate the stiffness of muscle and prepare the joint for

impending loads using the feedforward mechanism (da Fonseca *et al*., 2004, Johansson *et al*., 1991b, Dyhre-Poulse and Krogsgaard, 2000). This theory is more feasible as the joint afferents may provide continuous afferent signals and not just at extreme ranges of movement that inform preparation signals for impending loads (Ferell *et al*., 1987).

Although theories support a role for cruciate ligaments in proprioception, it is unclear exactly how much contribution can be accredited to knee joint receptors (Adachi *et* al., 2002, Johansson *et al*., 1991a) and surrounding muscle spindles (Riemann *et al*., 2002c) or indeed interaction between the two, for example in the "final common output" theory (Johansson *et al*., 1991b). Research is this area has been criticised for its indirect nature, for example considering sensory evoked potentials (SEPs) during unconscious palpation of tissues (Dye and Vaupel, 2000). Indeed the main body of literature comes from histological perspectives and is therefore lacking in ecological validity. However, it is evident that structures in the knee joint have the architecture to provide proprioception information during movement, and hence contribute to joint stability (Adachi *et al*., 2002). As such, it is likely all mechanoreceptors in and around the knee joint contributes to proprioception. The following section discusses the current protocols for the measurement of knee proprioception; hence the "net" proprioceptive ability of the knee joint, regardless of which classification of mechanoreceptors supplied the afferent information.

2.4.1 Measurement of Knee Proprioception

If we consider the complexity of each component of the sensorimotor system, it becomes clear that a valid measurement technique for any one anatomical area of this system (i.e. the knee joint) is difficult to address. Investigators have utilised a range of techniques to measure knee joint proprioception. Some researchers consider the pathway between mechanoreceptor afferent information and the cerebral cortex, investigating firing patterns of sensory evoked potentials (SEPs) after stimulation of a ligament (Courtney *et al*., 2005). Other researchers have simplified the problem by measuring the outcome (movement) of sensorimotor system processes only. These studies include measurement of laboratory based outcome measures such as joint kinematics and kinetics during gait analysis (Devita *et al*., 1998), muscular contraction patterns using electromyography (Houck *et al*., 2007) and postural control (Wikstrom *et al*., 2006). An alternative to these methods measure the ligament-muscle protective reflexes such as the ACL-hamstring contraction discussed previously (da Fonseca *et al*., 2004, Jennings and Seedholm, 1994; Beard *et al*., 1993). In clinical environments however, knee proprioception

has been divided into static and dynamic modalities. Static proprioception is concerned with the position of segments relative to other segments (Jerosch and Phymka, 1996a, Jerosch and Phymka, 1996b) and is measured using joint position sense techniques (Wikstrom *et al*., 2006). Dynamic proprioception identifies kinaesthesia (rate of movement) ability and is typically measured using threshold to detect passive motion techniques (Wikstrom *et al*., 2006, Beynnon *et al*., 2000). Suetterlin and Sayer (2014) have summarised the available types of clinical proprioceptive testing (see table four). The Foundation of Sports Medicine Education and Research workshop of 1997 identified joint position sense (JPS) and the threshold to detect passive movement (TTDPM) as the two most commonly used methods to quantify proprioception (Lephart *et al*., 2000). However, Stillman (2000) states "…*the average clinician, whilst now more aware of the significance of proprioception, does not appear to have significantly increased the frequency or quality of clinical proprioception assessments from the levels which applied at least 50 years ago*" (p.222).

Table 4. Types of clinical proprioceptive testing (adapted from Suetterlin and Sayer, 2014, p.314).

Name of test (proprioceptive sense tested)	How to perform	Specific cognitive requirements	Variables to control	Equipment needed
Toe position sense	Passive positioning of the toe into ventral and dorsiflexion	None	Distance moved, extraneous cutaneous stimulation	None
Ipsilateral remembered matching (JPS)	Position matching using the same limb	Intact working memory	Time to reference position, distance moved, dominance of side used, active / passive movement	Position measurement equipment
Contralateral matching (JPS)	Position matching using the opposite limb	Intact inter-hemispheric communication	Time to reference position, distance moved, dominance of side used, active / passive movement	Position measurement equipment
Contralateral remembered matching (JPS)	Position matching using both contra and ipsilateral limbs	Intact inter-hemispheric communication and working memory	Time to reference position, distance moved, dominance of side used, active / passive movement	Position measurement equipment
Kinaesthetic testing (Kinaesthesia/ TTDPM)	The limb or joint being tested is attached to a motor and the slowest movement detected by the participant is measured	None	Extraneous auditory and cutaneous stimulation	Specialised motor driven equipment, audio equipment, pneumatic sleeve
Dynamic position test (dynamic position sense)	Subject opens hand when elbow joint rotates through a pre-determined target position with eyes closed	Intact JPS and working memory	Dominance of side used, time to reference position	Video camera, specialised torque motor-driven equipment

Thumb finding sense (dynamic position sense)	Upper limb is placed in a target position, participant has to touch target thumb with other thumb with eyes closed	Intact JPS and inter-hemispheric communication	Time to reference position, distance moved, dominance of side used, active / passive positioning	None
Finger-nose test (dynamic position sense)	One / both limbs moved and participant touched nose with forefinger with eyes closed.	Intact JPS and inter-hemispheric communication	Time to reference position, distance moved, dominance of side used, active / passive positioning	None

The following sections critique knee joint position sense and knee threshold to detect passive motion or kinaesthesia only. These measurements will be considered separately as it is a common belief the processing of static and dynamic proprioception are two separate modalities (Elangovan *et al*., 2014).

2.4.2 Joint Position Sense

Knee joint position sense is measured using matching knee angle methods (Smith *et al*., 2012). This typical begins with vision being excluded (via closed eyes or a blindfold) and the knee joint being passively extended or flexed by the researcher or a machine, for example on an isokinetic dynamometer (IKD) (Carter *et al*., 1997) or self-constructed pulley system (Rehm *et al*., 1998) to a specific target angle. There is no standard direction of movement or target position; hence research has used both flexion and extension into a range of target angles moving through low to high ranges of motion. Angular velocities have also varied from 2°/s to uncontrolled (Beynnon *et al*., 2000). The leg is held in this position for 3-5s then passively returned to the starting position (typical 0° or 90° of knee flexion). The participant is instructed to replicate this angle and again, as there is no standardised technique, this has been done in a variety of ways. The most common is to ask the participant to actively move the same leg to the target angle and hold this position; this is known as passive active reproduction (PAR). However some studies have also considered passively moving the same leg (PPR) and stopping movement on the command of the participant either verbally or using a hold button (Katayama *et al*., 2004).

Other studies use a plastic handheld or computerised visual analogue of a leg or the contralateral leg to collect reproduction angles. However it is known matching error will increase when the target is reproduced using another part of the body or an external device (McCloskey, 1978, Rodier *et al*., 1991, Elangovan *et al*., 2014). This is due to the increase in required neural processing for cross-modal tasks (Reider *et al*., 1991). For example, the transfer of required information to mediate matching positions will increase, more processing stages are involved and more attention is used, therefore there is a higher probability of errors (Reider *et al*., 1991). Furthermore, Grob *et al*., (2002) consider the correlation coefficients between different PPR JPS techniques, analogue scale and contralateral leg procedures. Results indicated that there were no significant relationships between the three PPR techniques and hence techniques should not be used interchangeably.

The angle matching tasks can be executed in open kinetic chain sitting and/or prone positions (for example Co *et al*., 1993) and standing or closed kinetic chain positions (for example Kiefer, 1998). The closed kinetic chain task is a weight-bearing position and provides the opportunity to collect active target and active reproduction angles (AAR) under typical loading conditions (Bullock-Saxton *et al*., 2001). Partial weight-bearing conditions in which participants lie on a sliding platform and push off a stable surface to the target and reproduction angles (Bullock-Saxton *et al*., 2001) may also provide a more ecologically valid environment than non-weight-bearing and a more realistic task for unstable participants such as the elderly. However they have been used less frequently in the literature, perhaps due to difficulty in controlling the target positions.

Currently there is no consistent evidence base for the recommended number of trials for knee joint position sense. Although Selfe *et al*., (2006) stated consistent results may occur after completion of five or six trials depending on the outcome measure recorded. The only other study to consider the required number of trials is Piriyaprasarth *et al*., (2009). This study examines the learning effect on stroke patients and concludes it may be necessary to take ten trials to collect representative data from this population (Piriyaprasarth *et al*., 2009); however these patients will have both musculoskeletal and neurological deficits. Stillman (2000) concludes it is important an appropriate number of trials for accurate JPS representation is confirmed in the literature. There is also no information on how long the leg should be held in the target position. However it is suggested error matching scores worsen as the amount of time between target and matching angles increases (Xie and Urabe, 2014) and hence the time lapse between target and reproduction tasks should be minimal. This finding is disputed by Horch *et al*., (1975). They concluded knee joint position sense does not change with time; in fact memory of target position is still accurate up to 3 minutes after target joint positioning thus proprioceptive memory is good. However the knee joint must rotate a minimum of 3-4° before change is position is perceived (Horch *et al*., 1975).

Knee flexion or extension target and reproduction angles are typically measured using image capture, goniometry, electrogoniometry or isokinetic dynamometry (Smith *et al*., 2012). Indeed, Smith *et al*., (2012) recently published a review on JPS measurements with an aim to determine a reliable JPS measurement. The findings suggested that intra-rater reliability was dependant on data acquisition techniques; image capture produced greater reliability than electrogoniometery and dynamometry. There are limitations to some available JPS equipment (Stillman, 2000). For example the use of an IKD may produce abnormal afferent feedback for

two reasons; the first is caused by the joint being abnormally stressed if the axis is not aligned properly to the lever arm of the equipment. Secondly, the straps used to attach the apparatus can distort natural afferent feedback from cutaneous receptors. Goniometry also has its limitations; the size of the goniometer may not be suitable for every participant leading to measurement errors. Furthermore electrogoniometery and clinical goniometry is reliant on accurate placement of the device and assurance the device models the underlying axis of rotation accurately (Stillman, 2000). Finally visual analogue scales may not be ecologically valid when measuring JPS as it requires different neural processes to that of normal knee movement (Stillman, 2000). Nasseri *et al*., (2007) also found both automated tracking and manual goniometry from photos of knee motion to be reliable. However, it may be video analysis, which is less intrusive than other techniques is the optimal equipment for JPS measurement. Nevertheless, practitioners should appreciate JPS techniques are not correlated and should not be used interchangeably (Kiran *et al*., 2010).

Another issue regards how data has been measured; using relative, absolute and variation in error scores. Relative error scores provide information on direction and magnitude of error and hence details of overestimation or underestimation of the reproduction position. Absolute error scores supply only magnitude of error providing an overall ability to reproduce the target angle (Beynnon *et al*., 2000). Some investigators have used the standard deviation of error scores to present JPS precision (Beynnon *et al*., 2000). Due to this there is a lack of normative JPS values in the literature. Stillman *et al*., (2002) does provide normative values for 44 young adults using a passive-active reproduction sitting protocol of -0.8°±2.0 (mean relative error score±SD), 2.2°±1.2 (mean absolute error score±SD) and 2.0°±1.0 (mean variable error score±SD). Further, Ogard (2011) states normative JPS scores in the range of 0.7° to 6°. However, large scale normative and representative JPS scores have yet to be established (Stillman. 2000).

There are clear variations in JPS protocols, considering the neurophysiology previously discussed, each variation in method provides different JPS constraints. For example, during end of range knee joint motion it is known a higher percentage of ligament mechanoreceptors will be stimulated and the cerebellum subconsciously excites the antagonist muscles (Dye, 2000, Janwantanakul *et al*., 2001, Zimny, 1998, Matthews, 1987, Stillman, 2000). Hence it would be logical to conclude that if target angles are measured at the end range better error scores will be collected compared to mid and low range target angles. Starting position may also impact joint position sense ability (Lonn *et al*., 2000a); it is suggested that positions which

place the antagonist muscles around joints in a more elongated condition will improve proprioceptive ability due to a higher spindle firing rate from the start of the protocol.

Similarly, active-active reproducing protocols should elicit better JPS scores as neurophysiologically more mechanoreceptors are stimulated throughout the duration of the test (Andersen *et al*., 1995, Kiefer *et al*., 1998, Matthews, 1987) compared to passive-active reproduction protocols (Lonn *et al*., 2000a). Further to this point, Stillman and McMeeken (2001) provide evidence that weight bearing active-active reproduction protocols elicit smaller JPS error scores, potentially due to increased muscular mechanoreceptor activation as a result of increased muscle contraction in areas around the knee joint (including the gastrocnemius complex) to resist body weight. Active testing may also be precise as it involves increased input from the central nervous system (Evarts, 1981). For example, simple predictive active movement (such as knee flexion and extension) are enhanced by efference-copy based predictions in the cerebellum, distinct from alpha gamma motor neurone modulation of muscle spindles (Bhanpuri *et al*., 2013). In addition, closed chain tasks put more strain on knee ligaments (Fleming *et al*., 2001, Heijne *et al*., 2004) hence it would be expected more mechanoreceptor feedback would be initiated in JPS protocols of this type. Investigators also suggest active-active protocols increase ecological validity (Stillman and McMeeken, 2001). This is supported by Herrington (2005), Ghiasi and Akbari (2007) and Andersen *et al*., (1995) who concluded closed chain active-active reproduction protocols were more accurate than open chain procedures. Despite such findings Kramer *et al*., (1997) and Lokhande *et al*., (2013) found a standing JPS protocol produced greater error scores than unloaded conditions and hence may not be an optimal JPS environment. It is important to consider certain populations, such as patients with joint instability or the elderly, may not be able to complete weight-bearing knee flexion-extension tasks and therefore a partially loaded procedure may be more appropriate (Bullock-Saxton *et al*., 2001). However more reliability and validity analysis is needed in this type of JPS procedure. Unsurprisingly, closed and open kinetic chain tests are not significantly correlated and should not be used synonymously (Ghiasi and Akbari, 2007, Foch and Milner, 2013, Bullock-Saxton *et al*., 2001).

A final consideration for clinicians is the impact of a warm up prior to JPS collection. A warm-up is defined as a period of preparatory exercise to enhance performance (Fradkin *et al*., 2010). At the peripheral level a warm-up may improve the visco-elasticity of muscular tissue, increase nerve-conduction rate and increase body temperature which may improve proprioception (Ribeiro and Oliveira, 2011). At the central level increased corollary discharges and fusimotor

commands following a warm-up may improve muscle spindle sensitivity (Ribeiro and Oliveira, 2011). Although, research in this area is sparse compared to the literature on other measurement variables, it is hypothesised a warm up should improve knee JPS ability both at the peripheral and central levels (Subasi *et al*., 2008). Exercise may improve the muscle's visco-elastic properties, leading to more laxity (abnormal rotation or displacement of the tibia relative to the femur) around the joint. This may in turn increase the response of mechanoreceptors in the area and hence increase the sensitivity of these receptors which may improve JPS.

Other responses to exercise that may improve the function of mechanoreceptors are enhanced oxygenation by increased blood flow, increased nerve conduction rate and increased temperature because of vasodilation (Magalhães *et al*., 2010). At the central level, exercise at sub-maximal levels may increase corollary discharge and fusimotor commands followed by muscle spindle sensitivity thus preparing the nervous system for an effective response during JPS measurement (Bouët and Gahéry, 2000). However, despite these theories, evidence does not fully support the use of a warm up to enhance JPS. To date four studies have shown some weak supportive data. For example Bouët and Gahéry (2000) found 10 minutes of self-paced low intensity cycling improved JPS using one contralateral limb matching protocol, but three further measures of knee JPS were not affected by the warm up. It should be noted there was no control group and non-parametric statistics provided the conclusions. Bartlett and Warren (2002) also suggest that a warm-up can improve knee JPS acuity. However, again non-parametric statistics provide limited generalizability to the population of interest and JPS data were collected using a hand held knee model that has been criticised for its poor ecological validity. Subasi *et al*., (2008) and Magalhães *et al*., (2010) elected to use the more tradition limb repositioning techniques discussed earlier in this section. Both studies reported some improvement of knee JPS following a warm-up. Specifically, Subasi *et al.,* (2008) discovered a 10-minute warm-up period significantly improved some measurements of JPS taken using a passive replication tasks in an open kinetic chain position. Again, non-parametric data and small sample size limit these findings. Magalhães *et al*., (2010) also found JPS to improve but only in a closed kinetic chain environment and not in an open kinetic chain as in the study by Subasi *et al.,* (2008). Overall methods are inconsistent, results are conflicting and therefore it remains unknown as to whether a warm-up is needed prior to JPS collection.

The plethora of JPS measurement techniques in the current literature, although all providing a type of JPS measure, cannot be easily synthesised and hence results cannot be generalised. The lack of concurrent JPS methods may also be due to the minimal amount of consistent reliability

and validity research completed. Kramer *et al.*, (1997) reported moderate (0.40-0.75) intra-class correlation coefficient scores for both sitting and standing JPS scores taken from an asymptomatic population. Sitting provided higher reliability statistics than standing however standard error of measurements were relatively similar to JPS error scores; thus authors discussed the precision of JPS scores may be masked by error in measurement technique. This is supported by Kiefer *et al.*, (1998), who reported poor to modest intra-class correlation coefficient scores, concluding again that clinicians must consider measurement error in JPS scores, as they might mask JPS changes. Similarly Fatoye *et al.*, (2008) found knee JPS test-retest reliability to be poor to moderate. Marks (1994) reported the standard error of measurement of a sitting JPS protocol using an IKD ranged from 0.78°-1.06° which may well be in the range of JPS ability error scores.

Olsson *et al.*, (2004) reported fair to good intra-class correlation coefficients for one approach to JPS measurements using an electrogoniometer in sitting and prone positions. The good intra-class correlation coefficients results were from JPS in a sitting condition, using a mid-range target angle. Beynnon *et al.*, (2000) compared several JPS protocols, including closed and open chain tasks both in sitting and standing positions. In support of previous research, intra-class correlation coefficients ranged from poor to good; the most reliable protocol being a JPS standing condition. Interestingly, three studies that used Pearson's correlation coefficients rather than intra-class correlation coefficients to examine the test-retest reliability of knee JPS (Petrella *et al.*, 1997, Fischer-Rasmussen *et al.*, 2001, Mir *et al.*, 2008) all found strong relationships between session one and session two (r=0.88, r=0.8, r=0.99 respectively). However despite some promising outcomes it needs to be recognised studies used a range of equipment, both open and closed kinetic chains and also range of motions. As such it is very difficult to syntheses the reliability findings in this section.

Considering the current literature it is difficult to identify the most reliable method of JPS. This may be attributed to the inconsistent protocols used in current studies. Furthermore, Grob *et al.*, (2002) and Herrington *et al.*, (2005) found no significant correlation between different JPS protocols. It is critical that clinical practitioners have one reliable and valid JPS method confirmed to inform their practice. It is evident there is much variation in the techniques used to measure JPS (see appendix 1a and 1c) and as yet there is no clear standardised clinical method. With up to 12 decisions to make for each JPS measurement (warm-up, equipment, leg, position of participant, knee angle starting position, angular velocity, direction of movement, target angle, hold time, reproduction technique, number of trials, outcome measure) it may not

be surprising no "gold standard" technique has been agreed. In fact, the only aspects JPS protocols have in common is visual feedback is removed from the process, either via a blindfold or screen and measurements are conscious. Therefore the reliability of a methodology should be established for a range of knee angles, joints and age groups; for healthy, sedentary and physically active men and women and for those with joint pathology (Marks, 1994, Clark, 1992, Stillman, 2000).

2.4.3 Threshold to Detect Passive Motion.

There is more consistency among threshold to detect passive motion protocols; perhaps because the process is comparatively simpler. The participant is seated and the leg is passively moved, the participant must then indicate the detection and sometimes direction of this movement. This method was introduced by Goldsheider in 1889 and has been the main measurement of kinaesthesia ever since (McCloskey, 1978, Beynnon *et al.*, 2000). Investigators have used motion into knee flexion and extension but the angular velocity is normally approximately 0.5°/s. It is known that very slow speeds below 1°/min are not detectable and therefore should not be used in TTDPM testing (Stillman, 2000). Starting positions are not always consistent (see appendix 1a). The threshold to detect passive movement is typically measured using angular displacement (°) prior to conscious detection of passive movement (for example Valeriani *et al.*, 1999). A statistically significant increase of TTDPM tends to occur in the range of 0.5° to 1.5°; however the clinical significance of this increase is unknown (Ogard, 2011). Researchers have also used time elapsed (s) before conscious detection of passive movement (for example Lephart *et al.*, 1992).

Pincivero *et al.*, (2001) considered TTDPM in a prone position, using an isometric hold procedure. Participants were asked to respond isometrically in response to the arm of an IKD releasing the leg. Results indicated an improved TTDPM near the extreme ranges of motion; this follows the neurophysiological expectations discussed in the previous section. However, no reliability statistics were presented and as this is the only study to use an isometric response protocol, as such result should be generalised with caution.

Reliability data has been produced for the more traditional TTDPM methods. Boerboom *et al.*, (2008) considered reliability of TTDPM using a prone protocol; results indicated there were in fact significant differences between some variables across testing days. Therefore not all TTDPM protocols were deemed reliable. Ageberg *et al.*, (2007) presented moderate to good

intra-class correlation coefficients for TTDPM measurements collected using a self-built lever machine. Again, the results of this study are limited due to the difficulty clinicians have in reproducing purpose built machines for TTDPM testing. Beynnon *et al*., (2000) presented an intraclass correlation coefficient of 0.83 when considering test-retest reliability for a TTDPM protocol involving an IKD. Fatoye *et al*., (2008) also reported an intraclass correlation coefficient value of 0.83 for TTDPM using a purpose built machine. Fischer-Rasmussen *et al*., (2001) provide further support for good test-retest TTDPM reliability stating a Pearson's correlation coefficient r value of 0.9.

Threshold to detect passive motion protocols appear to be more consistent than joint position sense procedures, perhaps due to its relative simplicity. However, researchers still have to make up to six choices (equipment, position, leg, starting angle, direction, angular velocity) before data collection. As with JPS methods, this limits the generalisability of results across studies.

2.4.4 Summary

As has been argued there is no "gold standard" knee proprioception measurement technique (Beynnon *et al*., 2000, Lonn *et al*., 2000b, Laskowski, 2000, Ogard, 2011). Furthermore, there are no normative values of reliability and sensitivity statistics from knee proprioception measures (Lonn *et al*., 2000b). Methods chosen by researchers are inconsistent and varied by up to 12 variables. In addition both knee flexion and extension have been considered in JPS and TTDPM measurements; this is important as different muscles, tendons and ligaments will be most active and hence different amounts of mechanoreceptors will be active in particular directions. It is also important to note individuals will have different distributions of mechanoreceptors in tissues and perhaps have better proprioception in particular directions. Stillman (2000) also identified the role of gravity and hence perception of limb weight on proprioception measures; as limbs are moved from 90° to 0° the effect of gravity increases and so will perception of limb weight. Hence it is likely target position will affect knee joint proprioception (Stillman, 2000, Young *et al*., 1993).

It is also important to appreciate both JPS and TTDPM protocols measure the conscious appreciation of knee proprioception. It is yet to be confirmed the level of correlation and/or agreement between conscious and unconscious proprioception. However, Van Beers *et al*., (1998) suggests proprioception may be more precise during unconscious perception. There is no validated, reliable method of measuring knee proprioception components of the

sensorimotor system. To prevent injuries using pre-screening and justify and evaluate knee joint rehabilitation programmes, it is paramount a standardised knee proprioception technique is established. As Beynnon *et al*., (2000) states "*while the importance of proprioception as a clinical outcome measure is becoming well recognised, the best measurement techniques have yet to be defined*" (p.128). More recently, Suetterlin and Sayer (2014) claim there has been little progress in the assessment of proprioception using clinical techniques and more accurate clinical assessment of proprioception is "vital" (p.317).

2.5.1 Normative Proprioception Levels

Despite the lack of a standardised measurement technique studies have attempted to provide some information on the effects various participant factors have on proprioception. These include age, gender, BMI, physical activity levels and knee condition (other than ACL injuries). The following section will consider each one in detail.

2.5.2 Age and Proprioception

An increase in age inevitably brings about declines in neuromuscular and motor performance (Gilsing *et al*., 1995). The distribution of mechanoreceptors is thought to decrease with older age (McCloskey, 1978). Indeed joint position sense has been shown to become more accurate throughout childhood and adolescence, peak in young adulthood, then progressively decline after this (Goble, 2010). Using stabilometry measures and clinical balance testing, older adults (typically over 60 years of age) have reduced stability and balance ability (Riva *et al*., 2013, Fransson *et al*., 2004, Manchester *et al*., 1989, Woollacott *et al*., 1986, Hageman *et al*., 1995, Horak *et al*., 1989). However, as stated previously these measurement techniques incorporate visual, vestibular and somatosensory contributions to balance control. Authors have also presented data on increased H-reflexes in the elderly (Suetterlin and Sayer, 2014) however again this incorporates additional systems to the somatosensory system and proprioception. In order to understand the age decline of joint proprioception specific measurements such as TTDPM and JPS must be taken.

The majority of studies investigating age effects on proprioception have been cross-sectional, comparing differing age groups using either JPS or TTDPM methods (Ribeiro and Oliveira 2007). Kokmen *et al*., (1978) were the first to investigate aging effects; they considered the metacarpophalangeal and metatarsophalangeal joint kinaesthesia using a TTDPM procedure. The aging group (61 to 84 years of age) demonstrated a significantly higher threshold to detect

movement in the lower extremities compared to the younger aged (19 to 34 years of age) group. Skinner *et al*., (1984) considered another lower extremity joint; the knee. Joint position sense and kinaesthesia were both positively correlated to age ($p < 0.001$ for both measurements) indicating as age increases knee proprioceptive ability decreases. In agreement Pai *et al*., (1997) found a positive correlation between ages and knee JPS. Barrett *et al*., (1991b) also found a positive relationship between ages and knee JPS using a matching analogue scale technique. However, these studies did not compare statistical differences between age groups and so we cannot infer cause and effect with any certainty. Another study by Kaplan *et al*., (1985) examined knee joint position sense using contralateral and ipsilateral matching protocols on females under 30 years of ages and over 60 years of age. In support of other findings, the older group had poorer knee proprioception; this being particularly evident in the ipsilateral conditions. This may be due to deficiencies in memory, however no data were provided on this aspect. Similarly, Petrella *et al*., (1997) noted an age decline in knee JPS using another ipsilateral active matching method. Not all research has supported an age decline, for example Barrack *et al*., (1983) only stated a decline in knee kinaesthesia with aging not knee joint position sense.

Later research has provided additional support for age related declines in proprioception. Hurley *et al*., (1998) compared the knee JPS of young (mean age 23 years) middle aged (mean age 56 years) and elderly (mean age 72 years) groups using an electro-goniometer technique into both flexion and extension. Results indicated elderly participants had the worst JPS of the three groups and age was again positively correlated with acuity of JPS. As discussed previously, measurement of JPS may be influenced by weight-bearing. However, Bullock-Saxton *et al*., (2001) discovered elderly participants (60-75 years old) found it difficult to complete full weight bearing JPS protocols so also considered partial weight-bearing measurements. Results stated the elderly group were less accurate in JPS than middle-aged and younger groups in both conditions.

An age-related decline in upper extremity and other lower extremity proprioception has also been studied with comparable findings. Verschueren *et al*., (2002), Gilsing *et al*., (1995), Jordan (1978), Kalisch *et al*., (2012), Stelmach and Sirica (1986) and Adamo *et al*., (2007) all reported declines of either position sense or kinaesthesia in elderly populations.

The apparent age related decline in proprioception has been explained by theories from both the central and peripheral nervous system. With ageing there are changes to the sensory organs

themselves; muscle spindles reduce in diameter (Herter *et al*., 2014). Also, the muscle spindle capsular thickness increases in the majority of muscles (Swash and Fox, 1972, Herter *et al*., 2014, Ribeiro and Oliveira, 2007, 2010, Shaffer and Harrison, 2007, Miwa *et al*., 1995, Mynark and Koceja, 2001). This is due to an increase in collagen and fibrous tissue content arranged in the inner capsule (Swash and Fox, 1972, Miwa *et al*., 1995). There is also an increase in the fibrous tissue encapsulating groups of muscle fibres involving typically 10-80 extrafusal fibres (Swash and Fox, 1972). These changes in the muscle capsule cause an increase in stiffness and a reduction in the extensive ability of the primary endings (Miwa *et al*., 1995). This is turn causes a loss in ability to deform and hence reduced sensitivity of the spindle (Mynark and Koceja, 2001) which would ultimately reduce joint position sense and kinaesthesia.

Muscle spindle sensitivity may also be reduced because of changes in spindle composition (Suetterlin and Sayer, 2014, Herter *et al*., 2014). It is thought there is a loss of fast myosin heavy chain isoforms, axonal atrophy, axonal swelling and expanded end plates which cause denervation (Shaffer and Harrison, 2007, Suetterlin and Sayer, 2014, Miwa *et al*., 1995, Ribeiro and Oliveira, 2010, Mynark and Koceja, 2001). This decreases the nerve conduction velocity (Miwa *et al*., 1995, Tanosaki, 1999) by up to 34.3% (Mynark and Koceja, 2001) and hence makes the spindle less sensitive to stimuli.

There is also a reduction in the total number of intrafusal muscle fibres (particularly nuclear chain fibres) (Herter *et al*., 2014, Ribeiro and Oliveira, 2007, 2010, Shaffer and Harrison, 2007, Miwa *et al*., 1995, Mynark and Koceja, 2001) articular receptors (Aydoğ et *al*., 2006) and cutaneous receptors (Herter *et al*., 2014, Suetterlin and Sayer, 2014, Iwasaki *et al*., 2003). For example Liu *et al*., (2005) found a significant reduction in the number of nuclear chain fibres present in the biceps muscle of adults aged over 69 years old compared to a younger control group. Similarly, Iwasaki *et al*., (2003) found a decrease in the distribution per mm^2 and cross-sectional area of cutaneous receptors of the elderly. Aydoğ *et al*., (2006) also found significant reductions of ruffini nerve endings, pacinian corpuscles and Golgi-like tendon organs in the ligaments of aged rabbits. It is logical to assume a reduction in the total number of receptors in the peripheral system will reduce proprioceptive ability.

There is also evidence for changes in the central nervous system with aging. There appears to be losses in some aspects of the dendrite system (Ribeiro and Oliveira, 2010). For example, the total number of functioning motor neurons may reduce by up to 21% in some areas of the body between 71 and 80 year olds (Mynark and Koceja, 2001) and an average of 10% loss

between the ages of 20 and 90 years (Pakkenberg and Gundersen, 1997). The remaining motor units are larger and have signs of axonal atrophy resulting in a reduced nerve conduction velocity (Ribeiro and Oliveira, 2007). In fact motor nerve conduction velocity may reduce from 48.1 m/s to 44.2 m/s in adults over 60 years (Campbell *et al.*, 1973) because individual, larger motor units attempt to produce the same amplitude but at a slower speed. There is also some qualitative evidence to suggest a thinning of grey matter in post central gyrus areas (Herter *et al.*, 2014, Scheibel *et al.*, 1975). Therefore they may be an almost sequential pattern of deterioration of the central nervous system of the elderly; there is a progressive disappearance of cortical neurones, plus a thinning of the grey matter which results in a less effective central nervous system and ultimately a reduction in proprioceptive ability.

In summary, the majority of research supports the notion of a proprioceptive decline with aging. Because of this the deficit in the elderly knee JPS error scores may be up to 6.54° (Barrack *et al.*, 1993) and in TTDPM up to a 50% decline (Yan and Hui-Chan, 2000) when compared to younger groups. However, proprioceptive methods used are inconsistent and findings have not been compared to large scale normative data. Most studies explain proprioception deterioration with aging on two main mechanisms; changes in the peripheral nervous system and changes in the central nervous system. Table five summarises the anatomical, physiological, central nervous system and clinical changes that are thought to occur with aging (Shaffer and Harrison, 2007). However, it is still unclear which aspect or which combination of aspects causes the decline in proprioceptive ability. The available research suggests loss in muscle spindle function is more evident than motor unit function. Perhaps it may be that measurement of cortical activity is more difficult than peripheral function so there is less research on it. It is very difficult to clearly divide the effects of aging between central and peripheral as both systems serve each other in proprioceptive organisation. The reduction in muscle spindle sensitivity may be a result of supra-spinally medicated changes in the gamma drive (mediated by the central nervous system) to the muscle spindles themselves. In conclusion, it is probable the reduction in knee proprioception with aging is a result of both peripheral and central modifications.

Table 5. Age-related anatomical, physiological, central nervous system and clinical changes in proprioception (adapted from Shaffer and Harrison, 2007, p.197).

Model	Muscle Spindle Changes	Articular Receptor Changes	Central Nervous System Changes	Clinical Proprioception
Human	· Increased capsular thickness · Reduced spindle diameter in some muscles · Reduced number of total intrafusal fibres and nuclear chain fibres in some muscles, no change in number of nuclear bag fibres · Modifications in myosin heavy chain content · Alterations in distal sensory axons	· Reduction in all joint receptor types in some injured ligaments	· Thinning of grey matter · Reduction in the number of motor neurones · Remaining neurones are larger and have a slower nerve conduction velocity	· Reduction in JPS measurements · Reduction in TTDPM measurements
Animal	· Impaired spindle sensitivity with aging	· Reduction in pacinian, Ruffini's and Golgi tendon like receptors in older rabbits' ACLs · Reduction in joint receptors and afferent input in mice with OA.		

2.5.3 Gender and Body Mass Index and Proprioception

Due to the higher ACL injury rate of female athletes there has been a wealth of literature considering the effect of gender on ACL risk (for example Arendt *et al*., 1999, Voskanian, 2013). Researchers have considered neuromuscular control via kinematic and kinetic (Hewett *et al*., 2005), electromyography (Raunest *et al*., 1996) and knee joint laxity (Shultz *et al*., 2004) measurements to name but a few to explain the gender main effect on ACL injury risk. However there has been very little attention on the effects of gender on proprioception measures of either normative or previously injured participants (Nagai *et al*., 2012).

Gender differences may exist in the joint kinaesthesia of physically active populations (Rozzi *et al*., 1999a). However, Rozzi *et al*., (1999a) could only identify a difference moving in to knee extension, not flexion. Nagai *et al*., (2012) measured the effect of gender on knee TTDPM in the transverse plane. Females displayed diminished TTDPM in two out of four independent variables, namely towards internal rotation from both an internal and external rotation start position. Therefore females may be more at risk of ACL injury as they are slower to respond once the knee is in an "at risk" position that includes internal rotation and knee extension. However, it must be acknowledged that measurement in the transverse plane is difficult and hence research is very limited in this area.

One obvious difference between males and females is the occurrence of a menstrual cycle. Aydoğ *et al*., (2005) considered the effect of the menstrual cycle, specifically levels of oestrogen and progesterone, on active knee joint position sense to three different target angles using both extension and flexion. Results indicated the phase of the menstrual cycle (menstrual, follicular and early luteal) had a main effect on knee JPS. Specifically, females were less accurate during the menstrual phase in the majority of measurements. Daniusevičiūtė *et al*., (2012) found hormonal effects on knee joint position sense in both basketball players and non-athletic controls; both groups had better position sense in the ovulation phase. It may be that increased oestrogen levels interact with neurotransmitters in the brain and improve movement sense. Fridén *et al*., (2006) also researched females across three phases of the menstrual cycle; menstrual, ovulatory and pre-menstrual using a TTDPM of the knee protocol. These results indicated kinaesthesia was worse during the pre-menstrual phase compared to the other two phases. Although this difference was statistically significant, the mean difference was only 0.2°, so its clinical value can be questioned. Also, no correlation between hormone levels and joint kinaesthesia was found. Further no control group of males was used in the study design.

There is also some evidence that hormone levels do not affect joint proprioception. For example, Hertel *et al*., (2006) revealed that despite varying hormonal levels throughout the menstrual cycle, no difference in passive knee joint position sense was found. This finding is supported by Harriell *et al*., (2010); who also showed that neither knee kinaesthesia nor joint position changed across the menstrual cycle. Some studies suggest the menstrual cycle may influence joint proprioception by altering sensory evoked potential discharge or excitability of mechanoreceptors (Aydoğ *et al*., 2005) but it is not known how hormonal changes influence joint proprioception directly. The effect of the menstrual cycle on joint proprioception is still debated; hence it is not clear if gender will modify proprioceptive acuity. Furthermore discrepancies in findings may be due to the variation in proprioception methodologies used, the timing of measurements across the menstrual cycle and also lack of male control groups to ensure gender differences exist regardless of the menstrual cycle.

Researchers have also investigated the effect of pregnancy on joint proprioception. It has been suggested that pregnant women may have diminished knee joint position sense compared to non-pregnant controls (Bányai *et al*., 2009). Preetha *et al*., (2011) also compared ankle joint position sense of pregnant and non-pregnant women. Women who were pregnant in their third trimester had significantly worse ankle joint position sense than non-pregnant women. Deficiency in joint proprioception may be due to an increase in laxity in the joints during pregnancy caused by weight gain and an increase in relaxin hormone levels. Therefore if a gender difference exists it may be exacerbated by pregnancy. However, these studies had small sample sizes and therefore potentially low effect sizes and had no male control group. Therefore, it is difficult to generalise findings to the general population.

In conclusion there is only limited data on differences in knee proprioception between males and females. There is some evidence that hormonal changes during the menstrual cycle or pregnancy may influence joint proprioception. However, most studies have utilised non-parametric data limiting statistical power and generalizability. Also, importantly, no male control group was used in these studies. However, one study, Schmidt *et al*., (2013), did use a male control group and found no significant effect of gender on elbow joint position sense using a larger parametric sample (n=87). Given such findings the effects of gender on proprioception remain unclear.

Being overweight is correlated with a poorer quality of life and potentially life-threatening diseases (Wing *et al*., 2007). However, the author is only aware of two research articles to

consider the effect of mass, height or BMI on proprioceptive ability. The first, Paschalis *et al*., (2013), compared the knee joint reaction angle and position sense of overweight, underweight and lean female participants. The knee joint reaction angle measures the angular displacement covered before the participant can actively respond to the leg being transferred from passive support to no support whilst lying in a prone position (Paschalis *et al*., 2007, 2008, 2013). There was a main effect of BMI on proprioceptive ability; the lean group had better knee joint position sense and reaction angle than both overweight and underweight groups. Underweight participants may have reduced proprioceptive ability due to greater neuromuscular deficiencies in the included joint whereas overweight participants may have poorer proprioception due to changes in body geometry, joint laxity and postural stability (Paschalis *et al*., 2013). However, it is still unclear exactly how these factors reduced proprioceptive ability. The second paper, Kaya *et al*., (2014), considered overweight adults (BMI>29kg/m^2) with and without knee pain. Knee proprioception was measured using a specialised piece of equipment that allowed semi-loaded squats with visual feedback (Functional Squat System (FSS), Monitored Rehabilitation Systems, Haarlem, The Netherlands). Results indicated the overweight group with knee pain had poorer proprioception than the overweight group without knee pain; no control groups were used so it is difficult to use this data for any further predictions. Furthermore, it is difficult to compare results of both overweight groups with other studies due to the novel method of collecting proprioceptive ability. Also, detailed activity levels of the participants were not reported. It is difficult to make any conclusion on BMI and proprioceptive ability as there simply has been no research specifically on this topic of interest.

2.5.4 Regular Physical Activity and Proprioception

It is commonly accepted regular physical activity and exercise has many positive benefits to the physiological, muscular and neurological systems. Therefore, it follows that researchers have considered the effects of physical activity and exercise on proprioception. Following other research into proprioception, outcome variables include balance ability using centre of pressure measures to record proprioception acuity. For example, Shim *et al*., (2010) and Gauchard *et al*., (1999) considered the effects of a range of activities, namely Tai Chi (a traditional Chinese mind-body exercise), Yoga, soft gymnastics, running, cycling and swimming, on balance ability. Results confirmed participants who were regularly active had better balance than sedentary controls. Furthermore, those people participating in more position focussed sports such as Tai Chi, Yoga and soft gymnastics, had better balance ability compared to aerobic

based sports; however the exact mechanism for this increase in balance was not confirmed. The majority of participants considered in proprioception and physical activity are elderly (on average above 60 years) and as previously stated age may have a detrimental effect on proprioceptive ability, this can lead to an increased risk of falls and degenerative joint diseases (Van Heuvelen *et al*., 1998).

As stated elderly populations are also most commonly used in studies considering JPS and TTDPM outcome measures and Tai Chi is a popular activity of interest. Tsang and Hui-Chan (2003, 2004) found that elderly Tai Chi practitioners (>60years old) had better knee joint position sense when compared to aged matched sedentary controls. Elderly Tai Chi practitioners and golfers also may have comparable knee JPS to young healthy controls (Tsang and Hui-Chan, 2004) when JPS is collected using an IKD and passive-passive angle replication. Regular Tai Chi practice can also improve TTDPM in the ankle and knee joint (Li *et al*., 2008a, Xu *et al*., 2003). Elderly (>65years) Tai Chi practitioners had the lowest TTDPM in the ankle compared to aged matched elderly swimmers and runners and sedentary controls (Li *et al*., 2009, Xu *et al*., 2003). However, the same group was only better in knee flexion TTDPM, not knee extension when compared to the other groups. The authors attributed this to the most common position used in Tai-Chi, which has the knees flexed. Aside from Tai Chi, regular aerobic exercise programmes three times a week or more appear to improve weight bearing knee joint position sense (Petrella *et al*., 1997). Active adults aged 60 years or over had significantly better knee joint position sense compared to aged matched sedentary controls. The active elderly also had comparable ability to young sedentary people. However, the young active group had the best knee JPS out of the three groups. It should also be noted again the measurement protocol (fully weight-bearing) was too demanding for the two elderly groups, they were not able to weight-bear unaided during knee flexion and extensions. Therefore, knee JPS was collected differently in these groups; this is an obvious limitation of the study and hence application of the findings. Petrella's *et al*., (1997) study results are supported by Ribeiro and Oliveira's (2010) open kinetic chain knee JPS study on elderly and young groups. Again, exercising (aerobic, flexibility and strength training) older people had significantly better JPS ability to non-exercised older people and comparable results to non-exercised young. The evidence strongly suggests regular physical activity and exercise can attenuate the age related decline of knee joint proprioception.

Further supporting evidence shows kinaesthetic sense may improve after a period of physical activity and exercise training (Jacobson *et al*., 1997, Li *et al*., 2008a, 2008b). Li *et al*., (2008a)

reported a significant improvement in knee TTDPM into flexion and extension in an elderly population (>60years) following 16 weeks of Tai Chi training. However, ankle TTDPM was not improved; this may be explained again by the most common Tai Chi position that already focusses on knee flexion positions. Furthermore, Jacobson *et al*., (1997) provided evidence shoulder TTDPM in a younger sample group (aged 20-45 years) can be improved following 12 weeks of Tai Chi training. Moreover, six weeks of strength training, both loaded and using body weight, can improve both dynamic (TTDPM) and static (JPS) knee proprioception in older women (>65years) (Thompson *et al*., 2003). In this instance, proprioception was measured using a self-built device for TTDPM and electrogoniometer for JPS. More acute effects of training on knee proprioception in a young adult group were considered by Ju *et al*., (2011). Repetitive passive knee flexion and extension movements were applied to each participant 30 times at three different angular velocities (2°/s, 90°/s and 150°/s). At the two higher velocities knee JPS (passive-active repositioning) and TTDPM improved. This has implications on rehabilitation programmes as continuous passive movement is a common form of intervention. Overall, evidence suggests elderly and younger populations can modify their knee proprioceptive ability following physical activity training.

The majority of evidence indicates moderate and regular physical activity can improve knee proprioception. However, we know the total number of mechanoreceptors does not increase with exercise (Ashton-Miller *et al*., 2001) so other peripheral adaptations must occur. Morphological changes may take place in the muscle spindles, specifically reduction in the latency and increase in the amplitude of stretch reflexes (Hutton and Atwater, 1992). It may also be muscle spindle sensitivity is increased following the repetition of motor skills which increases reliance of afferent information during performance of a skill (Thompson *et al*., 2003, Ju *et al*., 2011). Muscle strength improves with regular physical activity and exercise; Petrella *et al*., (1997), Tsang and Hui-Chan (2003) and Thompson *et al*., (2003) postulate this increase causes more neuromuscular control over the movement and hence more efficient proprioception. However, improvements in muscular strength would only explain active measurements of proprioception.

It is theorised central adaptations also occur following participation in regular physical activity and exercise. It is accepted the brain has plasticity and as such adapts to regular experiences such as physical activity (Ju *et al*., 2011). The muscle spindle gain (the receptor output firing rate / magnitude of the input stimulus) is modulated via the gamma motor neuron route during repetitive movements of physical activity (Ribeiro and Oliveira, 2010, Tsang and Hui-Chan,

2003). Specifically, the muscle spindle output is increased during repetitive movements facilitating plastic changes in the central nervous system which over time increases the strength of the synaptic connection and modifies the organisation and number of connections among neurons in central pathways (Ribeiro and Oliveira, 2010, 2007, Tsang and Hui-Chan, 2003). This results in modification of the cortical maps and hence cortical representation of the joints and thus an improvement in proprioception.

It is important to state proprioceptive adaptations as a result of regular physical activity and exercise only occur in muscle mechanoreceptors as these are the only receptors that are centrally modulated (Thompson *et al.*, 2003). However, cutaneous receptors do respond to changes in temperature (Green, 1977, Inman and Peruzzi, 1961). As skin temperature increases excitation thresholds decrease and hence the reaction latency decreases (Inman and Peruzzi, 1961, Gescheider *et al.*, 1997). The amplitude of the impulse from cutaneous receptors may also increase with temperature increases (Inman and Peruzzi, 1961). However, these relationships are curvilinear, specifically an inverted U shape; the optimum condition for sensitivity of pacinian corpuscles found in the skin occurs at approximately 37°C (Green, 1977). Therefore, during physical activity and exercise in which temperature increases cutaneous receptors will be more sensitive. The only adaptation that may exist in the articular receptors following regular physical activity and exercise in an increase in joint laxity but this is more likely to occur as a result of longitudinal participation in elite level sport such as ballet (Grahame and Jenkins, 1972).

In conclusion, evidence indicates a positive effect of regular physical activity and exercise on knee proprioception. Whether this adaptation occurs peripherally or centrally or in combination is not yet known (Ashton-Miller *et al.*, 2001). However, as the muscle spindle sensitivity is dependent on both the input stimulus and the central efferent signals it would be intuitive to suggest it is most likely a combination of components that can improve proprioception.

2.5.5 Elite Athletic Populations and Proprioception

Proprioception literature has predominantly considered pathological populations, particularly following ligament injuries. However, there has also been some specific focus on athletic participants. It is hypothesised athletes may have heightened joint proprioception either due to extended athletic training and/ or innate capabilities that provide enhanced mechanoreceptor

sensitivity (Safran *et al*., 2001). We have seen evidence of this hypothesis with the use of exercise programmes to enhance proprioception in elderly populations (see section 2.5.4). Research has not only focussed on balance through measurement of postural stability (see Gautier *et al*., 2008, Kiefer *et al*., 2011, Hrysomallis, 2011, Perrin *et al*., 2002, Vuillerme *et al*., 2001, Golomer and Dupui 2000, Leanderson *et al*., 1996) but also proprioceptive measures. This section will mainly focus on direct proprioception measures using either JPS or TTDPM from athletic populations in accordance with the main thesis objective.

Lephart *et al*., (1996) and Barrack *et al*., (1984a, 1984b) were the first authors to consider the effect of athletic ability on knee proprioception. Their work used TTDPM measures to compare ballet dancers and gymnasts to non-athletic controls. This particular type of athlete has a combination of motor development and flexibility with an emphasis on constant joint awareness. Ballet dancers and gymnasts are also thought to have significantly different joint modifications, in particularly greater joint laxity, compared to norms (Grahame and Jenkins, 1972). Therefore, these athletes were considered to be a population of interest. Procedures were consistent between Lephart *et al*., (1996) and Barrack *et al*., (1984a, 1984b); they both used the same self-devised pulley system to collect data at approximately 0.5°/sec. Results of the studies also concurred, dancers and gymnasts had a reduced threshold to detect passive motion (improved kinaesthetic ability) compared to non-athletic control groups.

Barrack *et al's.*, (1984a) early study on ballet dancers also included JPS measurements with interesting results. It was found that professional ballet dancers demonstrated a greater error score and hence a lower static proprioceptive ability compared to controls. Barrack *et al*., (1984a) attributed this to the hypermobility of dancers which increases joint laxity; this may reduce position sense ability. Later, Euzet and Gahery (1995) investigated knee JPS of athletes participating in National or International gymnastics, dance, American football and archery. Three joint position matching tasks were conducted including one contralateral leg matching and two matching using a visual aid (computerised image on a screen). Pooled data revealed an enhanced JPS ability in the athletic population compared to matched controls. This is supported in work by Ribeiro and Costa (2001) with surfers using active and passive ipsilateral matching protocols. However, both studies were limited to small sample sizes and non-parametric data. Muaidi *et al*., (2009) explored the knee JPS of Olympic level soccer players (n=18) using a knee rotation matching protocol and parametric statistical analysis. In support of the majority of previous work on knee flexion and extension JPS, they concluded the athletes had better joint position sense acuity,

More recently Kiefer *et al*., (2013) measured knee, ankle and hip JPS and centre of pressure of 28 professional ballet dancers and controls. JPS measurements were taken using weight-bearing active position active reposition protocols. Using parametric statistical analyses it was found that dancers were superior to controls in all three joint positioning tasks. Interestingly there were no differences in centre of pressure results between the dancers and control groups. This importantly highlights researchers should not confuse global balance measures (such as centre of pressure) with proprioceptive ability. Han *et al*., (2013a) and Waddington *et al*., (2013) continued the research in to multi-joint JPS measurements in elite athletes. Data was provided by gymnasts, swimming, sports dancing, badminton and soccer athletes from ankle, knee, spine, shoulder and finger joints using a self-developed purpose built machine that had an automatic stopper set at specified target angles. Results followed previous findings; athletes had better joint position sense at all five locations compared to an external control group.

It might be expected elite level athletes would have better proprioceptive acuity compared to non-athletic populations perhaps simply due to increased muscle spindle activity and increased automated motor skills (Euzet and Gahery, 1995). Courtney *et al*., (2013) compared knee proprioceptive ability between two different types of athletes (moderate-activity fitness exercise versus high-activity skilled training) to identify which type of athlete has the most prominent proprioceptive ability. It was apparent high-activity skilled training athletes had improved knee kinaesthesia and therefore may have the highest level of proprioception at the knee joint. Unfortunately, only TTDPM was tested therefore we cannot generalise this finding to joint position sense. However, Lin *et al*., (2006) investigated the differences in JPS between elite tennis players, amateur tennis players and non-athletic controls using a closed-chain reposition method. In support of Courtney *et al*., (2013) the higher the skill level the better the proprioceptive (joint position sense) acuity.

Studies have also considered performance of elite athletes following a knee injury. Ribeiro and Costa (2001) compared injured athletes to uninjured surfers and external controls; the injured group produced the highest joint positioning errors and hence the lowest ability to detect knee joint position. However, groups were small (five or four) and the study lacked statistical power. Furthermore, no detail of the injuries was provided. Naseri and Pourkazemi (2012) investigated the effect of patellofemoral pain on knee JPS in University level athletes using weight bearing and non-weight bearing repositioning procedures. No differences between injured athletes and uninjured athletes were found in any JPS measurement. This is in contrast to ACL injured populations (see section 2.1.2).

Authors have also published data on the shoulder, trunk and ankle joint position sense of athletes with varied findings. For example Dover *et al*., (2003) assessed shoulder JPS of softball, soccer and track athletes and found throwing athletes increased error scores (had less joint position sense) than non-throwing athletes. Tennis players may also have heightened shoulder position sense (Boyar *et al*., 2007). Furthermore, Green *et al*., (2013) and Herrington *et al*., (2010) found no differences in shoulder JPS between previously injured (joint sprains and subluxations, muscular-skeletal strains and ruptures) compared to uninjured athletes, suggesting no significant changes to JPS following these types of shoulder injury. This is supported in lumbar position sense studies; athletes with lower back pain do not demonstrate diminished position sense when compared to uninjured athletes (Silfies *et al*., 2007). This suggests athletes are able to compensate for the potential loss of joint position sense following an injury and still have a heightened ability compared to untrained controls.

Other research studies have found higher shoulder joint position sense ability when comparing athletes to non-athletes (for example, Nohdehi-Moghadam *et al*., 2013; Ramsay and Riddoch, 2001; Herrington *et al*., 2010). Professional dancers may also have heightened ankle joint position sense when compared to matched untrained controls (Schmidtt *et al*., 2005, Kiefer *et al*., 2013, Han *et al*., 2014, Aydin *et al*., 2002, Li *et al*., 2009). There appears to be strong evidence to support the notion of a higher proprioceptive ability in athletic populations. However, again, synthesis of the results is not easy due to the varying methods of collecting proprioceptive data. As discussed in previous sections, varied protocols may be measuring different aspects of proprioception and this is a limitation of the literature.

Although difficult to summarise definitively, the results do suggest heightened position sense and threshold to detect passive motion ability of athletic groups when compared to non-athletic control groups. The explanation for this can be broadly divided in to two aspects; innate characteristics of successful athletes and adaptations following years of training. It is possible elite athletes are born with superior physiological and neural systems that causes a "natural selection" to high performance sports (Euzet and Gahery, 1995). However, enhanced joint position sense ability may be as a result of years of training. One result of such motor practice may be the development of muscle sensory receptors (muscle spindles) parallel to the development of muscle fibres (Ashton-Miller *et al*., 2001). This may be in the form of systematic increases in the fusimotor drive in challenging tasks and in the gain (the receptor output firing rate / magnitude of the input stimulus) to the central nervous system (Ashton-Miller *et al*., 2001). The type of motor learning that occurs in the learning process and training

of athletic populations might also enhance proprioceptive ability. For example, motor learning during training increases the efficiency of motor control by initial increases in task attention and relevant cues which over time eventually increases the autonomy of movements (Ashton-Miller *et al*., 2001, Meeuwsen *et al*., 1993). Furthermore, athletes become less dependent on the external cues of a task and use more information from internal sources such as joint position sense (Batson, 2009) thus making athletes more expert at neural processing of this afferent information. Indeed evidence suggests athletic training improves proprioceptive pathways both at the central and peripheral level (Ashton-Miller *et al*., 2001).

Centrally, neural mechanisms are improved through the increase of neural processing and facilitating of afferent information. Peripherally, mechanoreceptors become more sensitive, particularly in the muscle spindles. Furthermore, regular movement patterns across the joint's range of motion stimulate articular mechanoreceptors more frequently. Finally, athletes may be more attuned to the task itself during joint position sense or kinaesthesia testing. Research has indicated participants produce different afferent discharge patterns when asked to pay attention to a task compared to when no attention is shown (Meeuwsen *et al*., 1993, Hospod *et al*., 2007). Furthermore, athletes may be able to use this function more effectively and increase task attention during learning which in turn increases mechanoreceptor sensitivity (Hospod *et al*., 2007).

Despite this evidence, literature has failed to demonstrate significant correlations between years of training and joint position sense ability (Han *et al*., 2014). This can be explained by genetic constraints of the athlete that are biologically determined (Muaidi *et al*., 2009). It may well be athletes reach a saturation of proprioceptive ability at some point during their career. Indeed research has suggested proprioceptive ability cannot be trained in non-athletic populations and exercise may even reduce this ability (Ashton-Miller *et al*., 2001). It is also important to acknowledge some types of athletes may have increased joint laxity as a result of long term training which may actually reduce proprioception (Han *et al*., 2014). There is a lack of research investigating knee proprioception ability after an ACL injury on elite athletes and therefore it unclear if the potential increased proprioception ability in this population remains following an ACL injury. Indeed athletes do not appear to have proprioceptive deficits following patellofemoral pain (Naseri and Pourkazemi, 2012) or various shoulder injuries (Herrington *et al*., 2010) potentially due to compensation from adjacent joints. Therefore, the effects of training and ACL injury on kinaesthesia and joint position sense have yet to be confirmed.

2.5.6 Fatigue and Proprioception

There appears to be no consensus on the definition of muscle fatigue (Enoka and Duchateau, 2008). However, Rozzi *et al*., (2000) states muscular fatigue is an inability to maintain a power output or force during repeated muscular contractions due to changes in physiological processes and also psychological factors such as motivation and concentration. Fatigue can be categorised in to peripheral and central fatigue. Peripheral, also known as muscular fatigue refers to localised muscle fatigue, below the neuromuscular junction in the muscle and contractile mechanisms (Hiemstra *et al*., 2001). Central fatigue involves mechanisms above the neuromuscular junction (Hiemstra *et al*., 2001). Generally authors do agree on the result of muscle fatigue as a decline in performance or a "*…transient decrease in the capacity to perform physical actions*" (Enoka and Duchateau, 2008, p. 11). Recent discussion on proprioception suggests muscle spindles provide the dominant afferent discharge in mid-range joint movements (Proske and Gandevia, 2009). Therefore it follows muscle fatigue may negatively influence proprioceptive pathways. If proprioceptive ability is reduced with fatigue then this might result in an increased risk of injury. Indeed research has already demonstrated a large increase in sporting injuries in the final third of matches (Hiemstra *et al*., 2001).

Researchers have considered the effects of fatigue on more global proprioceptive measures such as postural stability and balance (e.g. Caron, 2003, Johnston *et al*., 1998). The effects of fatigue on the shoulder joint (e.g. Sterner *et al*., 1998, Chang *et al*., 2006, Pedersen *et al*., 1999, Iida *et al*., 2014), elbow joint (e.g. Fortier *et al*., 2010, Brockett *et al*., 1997, Allen and Proske, 2006) and ankle joint (e.g. Sandrey and Kent, 2008) have been considered. The majority of studies conclude fatigue negatively influences balance, posture and joint proprioception.

The effect of both central and local fatigue on knee joint position sense and kinaesthesia has also been examined. The most common exercise used to induce central fatigue is cycling (Roberts *et al*., 2004b, Bayramoglu *et al*., 2007, Lattanzio *et al*., 1997, Changela *et al*., 2012). Lattanzio *et al*., (1997) and Changela *et al*., (2012) used weight bearing knee joint position sense with goniometry to measure the effects of cycling to maximal exhaustion or 60% of maximal heart rate with a subjective score of 14-17 on the rate of perceived exertion (RPE) or Borg scale. Both studies concluded the cycling fatiguing protocols induced a reduction in joint position sense. Roberts *et al*., (2008) induced a fatigue state by asking participants to cycle at an "*energetic*" (p. 992) pace corresponding to 60 revolutions per minute until they achieved exertions of 14-17 on the RPE scale. Results indicated a reduction in joint kinaesthesia towards

flexion but not extension using TTDPM measurements at 0.5°/s. Conversely Bayramoglu *et al*., (2007) did not find a significant effect of cycling fatigue on either knee JPS or kinaesthesia, although the fatiguing protocol can be questioned. This consisted of only a 5min cycle at 35-45 revolutions per minute with no more than 100 beats per minute heart rate measurements. Although this protocol was justified for the population used (some had osteoarthritis and were elderly) it is perhaps presumptuous to define it as fatiguing.

Other central fatiguing protocols include match simulation (Ribeiro *et al*., 2008), running (Baharlue and Khayambashi, 2012, Miura *et al*., 2004, Skinner *et al*., 1986a) and walking (Givoni *et al*., 2007). A volleyball match simulation was used to fatigue 17 elite female players and knee JPS was measured using open chain extension protocols with video analysis pre and post exercise (Ribeiro *et al*., 2008). A RPE scale was used to ensure all players reached at least a 15 score post-exercise. JPS measurements increased and hence ability to detect knee position decreased following the volleyball match. This finding is repeated in a study using similar JPS measurement techniques but using running to fatigue protocols (Baharlue and Khayambash, 2012, Miura *et al*., 2004, Skinner *et al*., 1986a). Participants ran on a treadmill until they reached an RPE score of between 14-20 or heart rate values reached between 50% - 90% of the maximum heart rate (Baharlue and Khayambash, 2012) and JPS was taking pre and post exercise in one such study. Miura *et al*., (2004) used 5 minutes of treadmill running at 10 km/h with a 10% uphill gradient to induce general fatigue, heart rate was taken as an indicator of fatigue status. Whereas Skinner *et al*., (1986a) used intermittent sprinting and uphill running to fatigue participants. All studies using a running protocol found significant decreases in JPS ability despite using different JPS measurement techniques to the match-simulation study (Ribeiro *et al*., 2008). Downstairs and upstairs walking has also been shown to reduce joint position sense ability (Givoni *et al*., 2007). Fatigue was confirmed both subjectively using a visual analogue scale and objectively using an IKD to measure maximum voluntary contractions. Joint position sense ability was collected using a contralateral limb matching task on a purpose built machine in a sitting position. Despite again a difference in data collection, results concurred with other central fatiguing studies, JPS ability was reduced following a bout of concentric and eccentric contraction protocols. Furthermore this decrease in JPS was positively correlated with the loss of force in the same muscle groups; errors were larger when the fall in force was greater although this relationship was only seen when all data was pooled.

Research examining fatigue and knee proprioception has more commonly used peripheral or local fatiguing procedures (Allen and Proske, 2006, Rozzi *et al*., 1999b, Torres *et al*., 2010,

Skinner *et al.*, 1986a, Gear, 2011, Ju *et al.*, 2010, Miura *et al.*, 2004, Allen *et al.*, 2010, Ribeiro *et al.*, 2007, Stillman *et al.*, 1999, Ribeiro *et al.*, 2011, Paschalis *et al.*, 2007, 2008, 2013, Marks and Quinney 1993, Dieling *et al.*, 2014). Rozzi *et al.*, (1999b) considered joint kinaesthesia of men and women before and after exercise on an IKD which included maximal concentric extension and flexion movement until knee extensor peak torque had reduced to 25% of the maximum voluntary contraction at 180°/s. Joint kinaesthesia only significantly reduced in the women group moving into knee flexion, all other measures showed no effect of the fatigue protocol. Skinner *et al.*, (1986a) also failed to find a significant main effect for IKD fatiguing on joint kinaesthesia. However Torres *et al.*, (2010) did report a reduction in kinaesthesia 1 hour and 24 hours after an eccentric contraction fatiguing protocol on knee extensor muscles. Dieling *et al.*, (2014) also found significant reduction in knee joint kinaesthesia following 40 repetitions of knee flexion and extension at 180°/s on an IKD.

There is limited research into knee joint kinaesthesia and peripheral or muscular fatigue however there is more substantial research on joint position sense and muscular fatigue. For instance Torres *et al.*, (2010) examined the effect of fatigue on joint position sense and concluded the ability to detect knee position significantly reduced 1 hour, 24 hours and 48 hours after the exercise at both 30° and 70° knee angles. This suggests the consequences of fatigue may last longer than first expected. In the same year Allen *et al.*, (2010) used a purpose built machine to measure JPS before and after concentric contractions of knee flexors in a prone position until the maximum voluntary contraction reduced to 70% of the maximum performance. Position error data demonstrated a decrease in position sense ability towards the direction of the exercise that is fatiguing flexor muscles produces greater error in the flexion direction. This finding was repeated in a study in the elderly (Ribeiro *et al.*, 2007). Participants over-estimated knee positions towards extension following fatigue of flexors and extensors by 30 maximum voluntary contractions using an IKD. Absolute error also increased in this study. Later Ribeiro *et al.*, (2011) used the same fatiguing protocol to investigate whether the muscle group fatigue influences JPS. Both agonist and antagonist exercise produced a reduction in JPS in the direction of fatiguing. Furthermore the level of the fatigue does appear to influence position sense (Gear, 2011). Fatigue decreased positional sense ability when muscle groups were fatigued to 90% and 50% of maximal voluntary muscle contraction but not 70%; however a clear explanation for this was not provided. The effects of using an active or passive fatiguing protocol also may affect JPS; passive exercises do not appear to significantly damage the

muscle enough to induce a reduction in position sense (Ju *et al*., 2010, 2011). This is expected as muscle fibres will probably not be damaged by passive movement.

Paschalis *et al*., (2008, 2007) conducted single and repeated bouts of maximal fatiguing exercise and concluded JPS was significantly decreased following the first and second exercise period. However, reductions were not as significant following the second bout. This implies JPS reductions following fatigue may reach a plateau; future research is needed to clarify this finding. The Paschalis group have also examined the effect of fatigue on joint reaction angle. This variable measures the angular displacement covered before the participant can actively respond to the leg being transferred from passive support to no support whilst lying in a prone position (Paschalis *et al*., 2007, 2008, 2013). The group included this test as they stated it is important to measure the muscular response to an internal stimulus (loss of passive support). Results indicated local fatiguing protocols that included 5 bouts of 15 maximal concentric voluntary contractions increased the reaction angle of the knee. Force matching tasks have also been used to illustrate a reduction in knee proprioceptive acuity following local muscle fatiguing exercise (Paschalis *et al*., 2013, Torres *et al*., 2010).

Miura *et al*., (2004) fatigued knee extensors and flexors using 60 consecutive maximal concentric contractions at $120°/s$ but did not find a reduction in JPS despite significant increases in heart rate. However, peak torque did not significantly reduce and suggested that muscle damage was not severe enough to influence joint position sense. Stillman *et al*., (1998) also failed to find any differences in JPS following local fatiguing of the flexors and extensors using an IKD. More recently Dieling *et al*., (2014) provided more evidence to suggest peripheral or muscular fatigue does not reduce knee JPS ability; they investigated knee JPS of elite ballet dancers and matched controls, results showed no effect of fatiguing muscles using as IKD on JPS performance. Marks and Quinney (1993) also did not find a difference in JPS following concentric – eccentric quadriceps fatiguing; interestingly the control group who did no exercise at all had an improved JPS, suggesting a learning effect in this study. The authors suggested the lack of decline in JPS ability may be due to other proprioceptors such as the unfatigued muscle spindles and joint receptors may have the ability to compensate for the fatigued muscles. Furthermore, local fatigue may not negatively affect central nervous system areas prominent in proprioception such as the cerebellum (Marks and Quinney, 1993). Although other authors attribute findings to the fatiguing protocol; it not being demanding enough to reduce knee position sense rather than theorising local fatigue does not in fact reduce position sense ability. The discrepancy in findings on knee proprioception following fatiguing

may be due to variability in both the fatiguing protocol and the proprioceptive measurement. The fatiguing protocol can be at the peripheral or central level and in many different formats (e.g. match simulation, isokinetic contractions or cycling) and intensities. The intensities can be individualised for each participant or a general protocol. The proprioception measure can be kinaesthesia (TTDPM) or JPS, the potential for variability in these measurements has been previously discussed.

The research discussed used a variety of joint proprioception measurement techniques. However, the majority of research agrees fatigue at both general and local levels can reduce knee proprioceptive ability. The exact mechanism of this reduction is not clear. Three theories have been proposed; impaired excitation of motor units (Rozzi *et al*., 2000, Paschalis *et al*., 2007,2008, Ribeiro *et al*., 2008, Hiemstra *et al*., 2001, Hutton and Atwater, 1992, Lattanzio and Petrella, 1998, Fortier and Basset, 2012, Gregory *et al*., 2004, Hutton and Nelson, 1985, Djupsjöbacka *et al*., 1994, Hayward *et al*., 1991) increase in knee laxity (Changela *et al*., 2012, Skinner *et al*., 1986b, Roberts *et al*., 2004b, Lattanzio *et al*., 1997) and increase in pain (Fortier and Basset, 2012, Ju *et al*., 2010, Ribeiro *et al*., 2007). The first suggests the reduction in proprioceptive ability is due to impaired motor unit function caused by a reduction in the number of functioning sarcomeres following muscle fibre damage (Paschalis *et al*., 2007, 2008) or muscle acidosis caused by an increase in metabolites when fatigued (Fortier and Basset, 2012, Skinner *et al*., 1986a, Lattanzio *et al*., 1998, 1997, Changela *et al*., 2012, Ribeiro and Oliveira, 2011, Djupsjöbacka *et al*., 1994, Hayward *et al*., 1991).

Muscle fibre damage can also impair the excitation-contraction coupling of the motor unit (Rozzi *et al*., 2000) and modify the muscle spindle and central neural pathways (Hutton and Nelson, 1985). This has been shown to increase the threshold for muscle spindle discharge which can also change the alpha-gamma co-activation in the muscle units (Ribeiro *et al*., 2008). The spindle resting rate is also different following fatigue, as the resting discharge is proportional to muscle length, this can cause misinterpretation of muscle spindle afferents in the central nervous system and hence a reduction in proprioceptive ability (Gregory *et al*., 1999). Hutton and Nelson (1985) also demonstrated a reduction in sensitivity to stretch and an increase in response latency following fatigue in feline models. Therefore fatigue induced muscle damage can alter both afferent and efferent responses to movement and hence reduce knee proprioception.

It is commonly accepted fatigue causes an increase in intra-muscular metabolites and inflammatory substances (Ribeiro and Oliveira, 2011) and it is believed this can also cause failure of muscle spindles and Golgi-tendon organs (Lattanzio *et al*., 1997, 1998, Changela *et al*., 2012, Skinner *et al*., 1986a, Fortier and Basset, 2012). The metabolites and inflammatory substances have a direct impact on the afferent discharge patterns of muscle spindles (Ribeiro and Oliveira, 2011) for example there is increase muscle spindle sensitivity via the gamma-motor neurone pathway. This modifies the alpha-gamma co-activation patterns, the central nervous system therefore reduces the accuracy of motor control and may interrupt muscle stabilising activity information to joints and hence reduce stability (Roberts *et al*., 2004b). Whether the failure of motor units is caused by muscle spindle damage or acidosis, the outcome appears to be similar. The central nervous system response is affected by the change in afferent signals and therefore motor control becomes less stable.

Another theory to explain reduced proprioception is an increase in knee joint laxity (Changela *et al*., 2012, Skinner *et al*., 1986b, Roberts *et al*., 2004b, Lattanzio *et al*., 1997). It is clear no biochemical changes occur in the synovial joint fluid to cause disruption of afferent signals as with the muscle unit (Robert *et al*., 2003). Therefore it is thought the repetitive high loading rates during fatiguing protocols increases the plastic properties of the ligaments and hence they become less stiff (Skinner *et al*., 1986b). This again changes the relationship between afferent discharge and knee position which can disrupt proprioception.

The final theory suggested as to why fatigue reduces proprioception involves pain (Fortier and Basset, 2012). Fatigue induces nociceptor activation, and hence pain afferents are stimulated (Ju *et al*., 2010). This creates muscle soreness, which has been associated with reduced excitability of motor cortex and hence disrupted afferent and efferent signals causing a reduction in proprioceptive ability (Ribeiro *et al*., 2007). However there is much still to learn regarding pain pathways and hence this area needs further investigation.

Although it is unclear which explanation is the true cause of proprioceptive decline, it is obvious this reduction does occur following fatiguing exercise. In joint position sense research where relative error scores were taken, that is to identify the direction of the positional error, it is apparent participants over-estimated the target, or over-extended the joint. This has also been explained in a number of ways in the literature. The sense of effort theory is closely linked to the illusion theory (Fortier and Bassert, 2012, Givoni *et al*., 2007, Ribeiro *et al*., 2007). This involves the disruption of the relationship between sense of effort and force to joint position.

Further, when the joint is exercised there is an increase in the centrally driven activation rates on the motor units and an increase in the sense of perceived effort (Fortier and Basset, 2012). However, when the joint is fatigued the expected afferent feedback based on this previous positional and effort sense experience is related to a more lengthened muscle and hence the central nervous system misinterprets this increase in afferent feedback as a lengthened muscle (Allen *et al*., 2010). Therefore when the joint is repositioned in limb matching tasks it is overextended. This error can also be exacerbated by an increase in passive discharge rate (Paschalis *et al*., 2007) and an increase in muscle circumference which increase the activation of cutaneous receptors (Paschalis *et al*., 2008). In summary these findings indicate joint position sense may be centrally driven as directional errors were consistent.

It is important to explain the results of studies that found no change in proprioception following fatiguing exercise (Bayramoglu *et al*., 2007, Rozzi *et al*., 1999b, Stillman *et al*., 1998, Fortier and Basset, 2012, Marks and Quinney, 1993, Baharlue and Khayambash, 2012). One viable explanation is the fatiguing protocols were not severe enough to induce peripheral or central fatigue (Rozzi *et al*., 1999b, Bayramoglu *et al*., 2007, Stillman *et al*., 1998). For example, the anterior shear loads imposed on the knee joint during an isokinetic contraction at 180°/s are equivocal to that of walking and compressive loads equivalent to stair climbing (Kaufman *et al*., 1991). This suggests studies using isokinetic fatiguing may not create representative fatiguing of the joint. Central fatiguing protocols can also be unsuccessful. For example Skinner *et al*., (1986a) failed to find a significant decline in proprioception following a running protocol, however participants were Navy SEALS. The authors believed they had not successfully generated the effects of fatigue in their study. However, it has also been suggested joint kinaesthesia cannot be affected by fatigue as joint motion is modulated by joint and cutaneous afferents that may not be damaged by muscle fatiguing (Torres *et al*., 2010). Furthermore joint kinaesthesia may have separate neural pathways to joint position sense which would again imply different fatiguing pathways (Fortier and Basset, 2012).

Paramount to all of these discussion points is the method of measuring fatigue, which is variable between studies (Fortier and Basset, 2012). The state of fatigue was measured subjectively using soreness, RPE and analogue pain scales and objectively using blood analysis and acidosis measures and maximal voluntary contraction measurements. There is still much debate surrounding the optimal method of confirming a fatigue status thus making it difficult to consider the effects of fatigue on proprioception. Furthermore again there is no consistency

in proprioception measures. Practitioners are also unaware of the clinical significance of this potential decline in proprioceptive ability, currently no large scale normative data exists.

2.5.7 Osteoarthritis and Proprioception

Osteoarthritis (OA) is the most common type of arthritis with an estimated 15.8 million sufferers in the United States (Pai *et al*., 1997) and up to one third of 63-94 year olds are living with the condition. It is also the fourth leading cause of non-fatal burden in the world (World Health Organisation, 2002). The knee is the most common joint associated with the disease (Sharma *et al*., 1997). Unfortunately for sufferers there are a number of debilitating effects of OA. Structural changes cause an increase in the regional load across articular cartilage in the joint and this negatively influences the material properties of the tissue and hence reduce the joint's ability to withstand load (Pai *et al*., 1997). There is often reduced stability in the knee of OA sufferers potentially caused by changes in the bony geometry, muscular contraction patterns and ligament and capsule deficiencies in and around the joint (Pai *et al*., 1997). As anatomy of the knee changes with OA progression and this is thought to reduce proprioceptive ability, research has considered the effect of OA on knee proprioception using both JPS and TTDPM techniques.

Research strongly suggests patients with OA have an increased threshold to detect passive motion (Pai *et al*., 1997, Sharma et *al*., 1997, Koralewicz and Engh, 2000, Collier *et al*., 2004, Lund *et al*., 2008, Hewitt *et al*., 2002, van der Esch *et al*., 2007, 2013, Cammarata *et al*., 2011, Chang et *al*., 2014, Sanchez-Ramirez *et al*., 2013). The severity of OA in these patients ranged from grade 1 to grade 4 (Kellgren/ Lawrence grading). Most studies used either a custom built machine or an IKD to collect flexion and/ or extension TTDPM data. However, Chang *et al*., (2014) considered valgus / varus movement. All studies used aged matched controls. Interestingly, studies that also included comparisons to the contralateral knee in OA patients reported a reduced TTDPM ability compared to external controls and no significant difference compared to the OA knee (Sharma *et al*., 1997). This suggests the undiagnosed knee may also have proprioceptive impairments.

As well as differences between groups, studies also considered the relationship between kinaesthesia sensibility and other OA characteristics. For example, Cammarata *et al*., (2011) Hewitt *et al*., (2002) and van der Esch *et al*., (2007) found no correlation between TTDPM measures and stiffness, age, gender, pain or WOMAC (Western Ontario and McMaster

Universities Arthritis Index) scores. Koralewicz and Engh, (2000) found no relationship between severity of OA (measured by radiography) and TTDPM ability. However van der Esch *et al*., (2013) did find an inverse relationship between number of lesions in the knee of OA patients and TTDPM; that is as the number of lesions increased, kinaesthetic sense decreased. Furthermore TTDPM ability has been linked to functional tests such as single leg balance (Sanchez-Ramires *et al*., 2013), activity levels (Holla *et al*., 2012) and walking times (van der Esch *et al*., 2007). The relationship between TTDPM and function was stronger if muscle strength was added to the regression model (van der Esch *et al*., 2007).

Studies have also considered the effect of OA on knee JPS (Garsden and Bullock-Saxton, 1999, Hurley *et al*., 1997, Mohammadi *et al*., 2008, Bayramoglu *et al*., 2007, Marks *et al*., 1993, Barrett *et al*., 1991b, Hassan et *al*., 2001, Bennell *et al*., 2003, Hall *et al*., 2006, Segal *et al*., 2010, Felson *et al*., 2000, Sanchez-Ramirez *et al*., 2013). All JPS protocols involved target and reproduction angles. However, there are many differences in other measurement variables such as weight bearing / non weight bearing conditions (for example Marks *et al*., 1993), matching methods (for example visual analogue scale in Barrett *et al*., 1991b) or active matching (Marks *et al*., 1993, Hall, 2006), equipment (for example electrogoniometery in Mohammadi *et al*., 2008) or IKD (Bayramogku *et al*., 2007). However, this variability did not appear to influence findings; the majority of research indicated patients with OA have reduced JPS ability. However Hall *et al*., (2006), Lund *et al*., (2008) and Bayramogku *et al*., (2007) did not find a difference in JPS between OA patients and age matched controls. They attributed this finding to a potential degeneration of the elderly control knees without diagnosis, lack of severe grade OA patients in the sample or lack of sensitivity of the measurement tool. Alternatively, it may be that JPS does not reduce with OA and the reduction in JPS ability preceded the disease (Lund *et al*., 2008).

The effect of OA on JPS was also considered using regression analyses. There were no relationships between JPS ability and pain, clinical scores or walking speed, (Marks *et al*., 1993, Bennell *et al*., 2003). Indeed Hassan *et al*., (2001) concluded the most significant predictors of OA progression were BMI and maximum voluntary quadriceps contraction. This is supported by Segal *et al*., (2010) who concluded knee JPS is not a valid predictor of OA condition alone. However, Felson *et al*., (2000) did find correlations between JPS and pain and WOMAC scores in OA patients that is as JPS ability got worse, so did pain and WOMAC scores across a 30 month period. It must be noted correlation analysis alone cannot provide

cause and effect and regression analysis only explains a certain amount of variance in the data, therefore findings must be generalised with caution.

It may be joint effusion of OA knees that prevents optimal JPS performance. However, there is only limited evidence to support this. McNair *et al*., (1995) considered the effects of injected saline into uninjured knees and concluded the artificial effusion did not reduce JPS ability. Conversely Cho *et al*., (2011) concluded OA patients injected with saline did have reduced JPS ability, but only is non-weight bearing conditions. Therefore it is still unclear what effects, if any, joint effusion has on proprioception.

Unfortunately, there are many negative consequences of OA. These include tenderness, limited range of motion, effusion or inflammation and most commonly, sustained joint pain (Kaya, 2014). Radiographic analysis of the pathological joint can further reveal asymmetric joint space narrowing, cyst formation, osteophyte formation and subluxation effects of the disease (Kaya, 2014). It is suggested the three consequences most likely to influence proprioception ability are impaired articular mechanoreceptors and hence modulated afferent discharge, muscle weakness that reduces gamma motor neurone activation and muscle sensitivity, inflammation / effusion and injuries to other structures in the joint such as meniscus (Knoop *et al*., 2011). These variables may all contribute to modifying the articular afferent discharge and hence joint proprioception which in turn may reduce function. However the research discussed is that of retrospective design and it cannot be deduced if the disease caused the proprioceptive design or poor proprioceptive ability preceded the onset of OA. OA progression certainly has a linear relationship to degeneration of the articular tissues, hence it would follow articular mechanoreceptors would be damaged and afferent signals would be modulated (Lund *et al*., 2008). This may reduce the sensitivity of the gamma motor neurones and then proprioception. On the other hand there is some evidence to suggest patients with OA may have had decreased proprioceptive ability prior to the disease diagnosis (Cammarata *et al*., 2011). Indeed contralateral knees and upper limb joints of OA patients have been shown to have decreased proprioceptive ability compared to uninjured matched controls (Sharma *et al*., 1997, Lund *et al*., 2008). Furthermore, it is thought up to a third of women with unilateral OA will have bilateral OA within two years of diagnosis (Garsden and Bullock-Saxton, 1999) and there is up to a 90% contralateral OA risk within 10 years (Jones *et al*., 2013). Despite these theories, a recent narrative review on proprioception and OA (Knoop *et al*., 2011) could not find any clear evidence to link impaired mechanoreceptors, reduced muscular strength and hence reduction in spindle sensitivity or inflammation in OA patients to the decline in joint

proprioception. There has been some correlation analysis on proprioceptive ability and decreased functional ability; however the evidence is far from extensive.

Whether the disease is in fact the cause or effect of reduced proprioception will need to be considered in more detail using longitudinal study designs in future research. However, importantly and in continuation of other sections in this literature review, the methodologies used to collect joint position sense and threshold to detect passive motion data were inconsistent; a wide range of equipment, angular displacements, angular velocities and angular directions were used to name but a few of the method variables. Importantly studies also found patients with OA were not always able to complete fully weight bearing testing. Therefore it is important a standardised method is identified to measure knee proprioception before these longitudinal studies can take place. There was also a lack of normative data on either knee joint position sense or threshold to detect passive motion.

2.6 Thesis Aims and Hypotheses

A flow chart below (see figure three) details the findings of each section of the literature review. This provides a rationale for each of the aims that follow. Some hypotheses can now also be made based on the available literature. There was no high quality literature available that would help predict the methodological aims, therefore the population aims are considered only.

The Effect of ACL injury on

Knee Proprioception: A Meta Analysis

Aim: To investigate the effect of ACL injury on knee proprioception.

Findings: Two main proprioception measures are JPS and TTDPM. JPS are more consistent than TTDPM. However, measures are inconsistent, lacking in reliability and validity statistics and therefore results are difficult to summarise. Inconclusive.

Literature on proprioception

Aim: To define proprioception.

Findings: There is a complex neurophysiological explanation of static and dynamic proprioception. Mechanoreceptors in muscle, joint and skin may all contribute different afferent information to the CNS.

Literature on knee proprioception

Aim: To relate propriception neurophysiology to the knee joint.

Findings: There is evidence mechanoreceptors are present in the knee joint as well as musculature surrounding the joint. However, it is unclear how each anatomical area contributes to knee proprioception.

Literature on knee proprioception measures

Aim: To state the current knee proprioception measurement techniques.

Findings: Although the literature offers a range of knee proprioception measurement techniques, there is not a comprehensive reliable and valid "gold standard" clinical method of knee JPS.

Literature on age, gender, BMI, physical activity, knee condition, fatigue and knee proprioception

Aim: To state the current understanding of the effects of various independent variables on knee proprioception.

Findings: Current literature does not consider large scale UK populations. There is a lack of data on fatigue and knee proprioception using consistent measurement techniques.

METHODOLOGICAL AIMS:

1. To establish a measurement technique that produces the best representation of knee joint position sense ability.

2. To establish a reliable, consistent and sensitive measurement of knee joint position sense.

3. To establish a valid measurement technique for knee joint positioning.

4. To establish the number of trials required for consistent knee joint position sense.

POPULATION AIMS:

1. To collect normative knee joint position sense from a UK population.

2. To consider the effects of age, gender, BMI, physical activity and self-reported knee condition (including OA) on joint position sense.

3. To compare the knee joint position sense of ACL deficient patients to matched controls.

4. To compare the knee joint position sense of patients with other knee injuries (not ligament) to matched controls.

5. To consider the effect of peripheral fatiguing exercise on JPS.

Figure 3. A summary of findings from the literature review and the aims of the thesis.

Population Group Aims and Hypotheses

Aim 1. To collect normative knee joint position sense from a representative sample of the UK population.

Hypothesis 1. An absolute error score above 5° may indicate abnormal knee joint position sense.

Aim 2. To consider the effects of age, gender, BMI, physical activity and self-reported knee condition on knee joint position sense.

Hypothesis 2. As age and BMI increase knee joint position sense ability will decrease. There will be no effect of gender on knee joint position sense. As physical activity and knee condition levels increase knee joint position sense ability will increase.

Aim 3. To compare the knee joint position sense of anterior cruciate ligament deficient patients (both non-athletic and elite athletic) to an uninjured matched control group.

Hypothesis 3. ACL patients will have reduced knee joint position sense ability.

Aim 4. To compare the knee joint position sense of patients with any other knee injury (not including ligament damage) to an uninjured matched control group.

Hypothesis 4. Knee injury patients will have reduced knee joint position sense.

Aim 5. To consider the effect of peripheral fatiguing exercise on knee joint position sense.

Hypothesis 5. Peripheral/ muscular fatigue will reduce knee joint position sense ability.

Chapter 3 Methodology

3.0 Introduction

This chapter is divided into measurement and population studies in knee joint position sense. The preliminary studies considered the "optimum" method of knee joint position sense. The results of the meta-analysis (Relph *et al*., 2014) indicated joint position sense to be a more consistent measure of knee proprioception. Therefore, joint position sense (static proprioceptive ability) is considered in this thesis and TTDPM (dynamic proprioception) is not. Literature also suggested injured and elderly patients found it difficult to complete fully weight-bearing conditions in JPS data collection and therefore these studies recommended either partial weight-bearing or non-weight-bearing environments for JPS data collection (Bullock-Saxton *et al*., 2001, Petrella *et al*., 1997). Therefore, JPS data collected in a fully open chain or partially open chain environment were explored. These environments included sitting (Co *et al*., 1993, Beynnon *et al*., 2000), prone (Kramer *et al*., 1997) and a partially weight-bearing condition with the participant in a supine position pushing against the wall on a sliding platform. This is a novel approach to JPS data collection that attempted to provide a realistic JPS data collection environment for all populations (including the elderly and injured) and incorporating an active-active protocol that may produce more ecologically valid results (Herrington, 2005, Ghiasi and Akbari, 2007, Stillman and McMeeken, 2001).

The first study considered the test-retest reliability of knee joint position measurements in sitting, prone and semi-weight-bearing conditions. The second study examines the inter-rater and intra-rater rater reliability of the data analysis technique. The third study reported the learning effect in knee joint position sense measurements and hence determined the required number of trials for a consistent result. The fourth study considered the consistency, sensitivity and hence "optimum condition" for knee JPS by examining the effects of condition, leg, direction and target angle on the data. The final measurement study investigated the construct validity of knee joint position sense measurement.

Following these initial studies, the optimal technique was used to collect normative knee JPS data on different populations. The first of this group of studies reported the normative knee joint position sense ability of a representative UK population. Included in this study was an analysis of age, gender, BMI, physical activity, self-reported knee condition (including OA) and knee JPS. Two further studies examined the effect of an ACL injury on knee joint position sense in non-athletic and elite athletic populations. In comparison, the next study reported the

effect of other knee injuries not including ligament damage on knee JPS. Finally, the effects of a peripheral or muscular fatigue protocol on knee joint position sense was reported.

3.1 The Test-Retest Reliability of Clinical Knee Joint Position Sense Measurement.

Participants

Ten healthy participants (five female; age 28.4±10.50 years, mass 59.4±5.86 kg, height 1.63±0.03 m, BMI 22.7±2.56, General Practitioner Physical Activity Questionnaire (GPPAQ) score range Inactive – Active, Tegner 5.8±2.17, Knee injury and Osteoarthritis Outcome Score (KOOS) 99.9±0.27, Lysholm 98.0±4.47 and five male; 32.0±7.65 years, mass 83.7±18.73 kg, height 1.80±0.08 m, BMI 26.0±5.51, GPPAQ range Moderately Inactive – Active, Tegner 4.8±3.03, KOOS 97.8±4.37, Lysholm 95±11.18) took part in the study using convenience sampling. All were free from lower extremity injury and neurological disease. Participants read an information sheet and provided written informed consent (see appendix two and three). This study was approved by the university ethics board (Ref 09/25).

Procedures

Participants wore shorts and removed their socks and shoes. The participants were prepared for data collection by placing markers on the following anatomical points; a point on a line following the greater trochanter to the lateral epicondyle, close to the lateral epicondyle (placement of a marker directly on the greater trochanter is difficult due to clothing), the lateral epicondyle and the lateral malleolus of both legs (following Andersen *et al*., 1995).

Sitting Condition

The researcher gave a demonstration of the JPS protocol before data collection to ensure the participant knew the detail of the protocol and hence felt comfortable being blindfolded during the testing. No warm-up was required as the procedure moved the leg through a "normal" (Palastanga and Soames, 2012) range of motion at a low angular velocity and hence it was felt there would be no risk of musculoskeletal injury. The participant was then seated on the end of a physiotherapy plinth (see figure 4) and blindfolded. Each leg was passively moved by the researcher through either 10°-30°, 30°-60° or 60°-90° of knee flexion (from a starting angle of 0°) or knee extension (from a starting angle of 90°) to a target angle at an angular velocity of approximately 10°/s (Marks and Quinney, 1993). The order of the target angles was randomly allocated using randomly generated numbers. The participant then actively held the leg in this position for 5s. A photograph of the leg in the target position was taken (see figure four) using a standard camera (Casio Exilim, EX-FC100, Casio Electronics Co.,Ltd. London, UK) placed

3m from the sagittal plane of movement on a fixed level tripod (Camlink TP-2800, Camlink UK, Leicester, UK). The camera was set up following the British Association of Sport and Exercise Sciences (BASES) guidelines (Payton, 2008). Perspective error does not affect measurement of angles (Payton, 2008) however; the camera was positioned as far from the field of view as possible and zoomed to an appropriate image size (Payton, 2008). Parallax error was reduced by ensuring the camera lens was positioned orthogonally to the field of motion (Payton, 2008) using spirit levels, a plumb line and measurement of a 90° angle between the plane of motion and the centre of the camera lens (Payton, 2008). The leg was then passively returned to the starting angle and the participant was instructed to actively move the same leg to the target angle and instructed to hold the leg in this position. Another photograph was taken and the participant instructed to move their leg back to the starting position. The process was repeated 15 times for each target angle on both dominant and non-dominant legs. The protocol was then repeated seven days later.
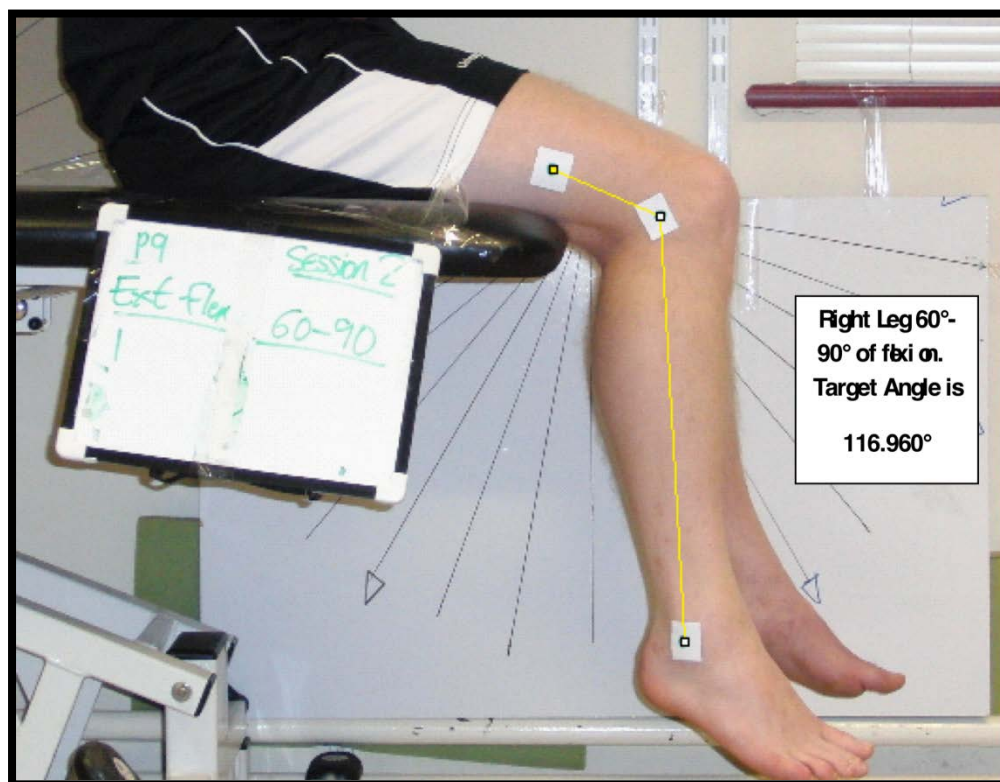
Figure 4. Typical set up and measurement of knee joint angle for sitting JPS measurements.

Prone Condition

The researcher gave a demonstration of the JPS protocol before data collection to ensure the participant felt comfortable being blindfolded during the testing. No warm-up was required as

the procedure moved the leg through a "normal" (Palastanga and Soames, 2012) range of motion at a low angular velocity and hence it was felt there would be no risk of musculoskeletal injury. The participant was positioned prone on a physiotherapy plinth and blindfolded. Each leg was passively moved by the experimenter through either 10°-30°, 30°-60° or 60°-90° of knee flexion (from a starting angle of 0°) or knee extension (from a starting angle of 90°) to a target angle at an angular velocity of approximately 10°/s (Marks and Quinney, 1993). The order of the target angles was randomly allocated using randomly generated numbers. The participant then actively held the leg in this position for 5s. A photograph of the leg in the target position (see figure five) was taken using a standard camera (Casio Exilim, EX-FC100, Casio Electronics Co., Ltd. London, UK) placed 3m from the sagittal plane of movement on a fixed level tripod (Camlink TP-2800, Camlink UK, Leicester, UK). The camera was set up following the British Association of Sport and Exercise Sciences (BASES) guidelines (Payton, 2008). The leg was then passively returned to the starting angle and the participants were instructed to actively move the same leg to the target angle. Another photograph was taken and then the participant was instructed to return the leg to the starting position. The process was repeated 15 times for each target angle on both dominant and non-dominant legs. The protocol was then repeated seven days later.

Figure 5. Typical set up and measurement of knee joint angle for Prone Condition JPS measurement.

Active Condition

The researcher gave a demonstration of the JPS protocol before data collection to ensure the participant felt comfortable being blindfolded during the testing. The participants were positioned supine on a "Total Trainer" (Model TT2500P, Bayou Fitness, Louisiana, USA) (see figure six and seven) and blindfolded. The "Total Trainer" equipment was set at a level 1 incline, providing 10% body weight (BW) resistance. This incline was selected after an initial pilot study revealed this incline provided an appropriate level of resistance for both flexion and extension trials. Each leg was actively moved by the participant through either 10°-30°, 30°-60° or 60°-90° of knee flexion (from a starting angle of 0°) or knee extension (from a starting angle of 90°) using the sliding seat on the "Total Trainer" at approximately 10°/s (Marks and Quinney, 1993, Bullock-Saxton *et al.*, 2001). The order of the target angles was randomly allocated using randomly generated numbers. For knee flexion trials, the participants were instructed to actively contract into flexion until verbally told to stop by the experimenter and hold in that position for 5s. For extension trials participants were told to actively contract against the wall and extend their leg until verbally told to stop by the experimenter and hold this position for 5s. A photograph of the leg in the target position (see figure seven) was taken using a standard camera (Casio Exilim, EX-FC100, Casio Electronics Co., Ltd. London, UK) placed 3m from the sagittal plane of movement on a fixed level tripod (Camlink TP-2800, Camlink UK, Leicester, UK). The camera was set up following the British Association of Sport and Exercise Sciences (BASES) guidelines (Payton, 2008). The leg was then returned to the starting angle by the participant using a verbal cue from the experimenter when to stop. Then the participant was instructed to actively move the same leg to the target angle without verbal cues. Another photograph was taken. The process was repeated 15 times for each target angle on both dominant and non-dominant legs. The protocol was then repeated seven days later.
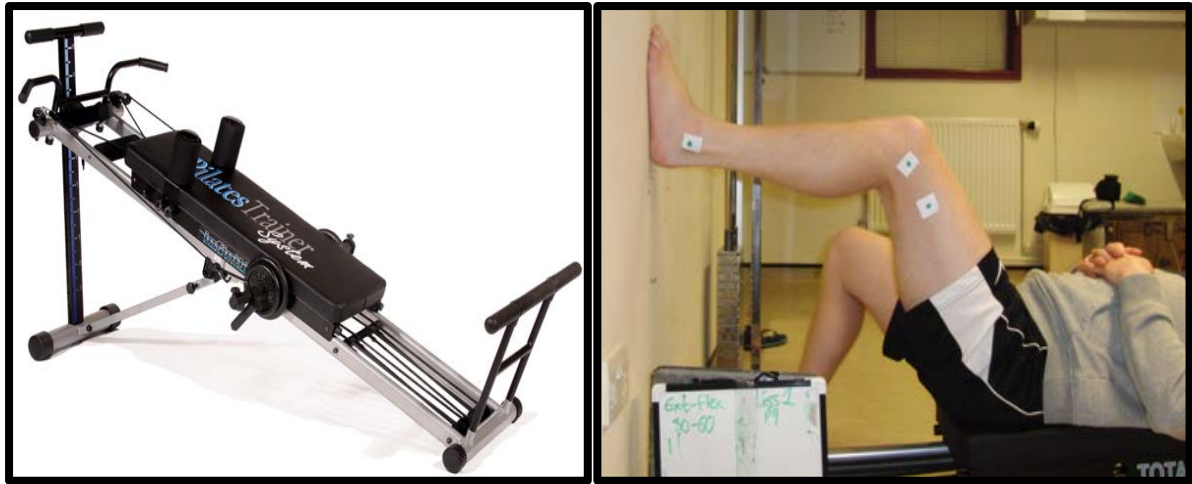
Figure 6. The Total Trainer Pilates Equipment, model TT2500P and an example of a participant on the equipment during collection of knee JPS.
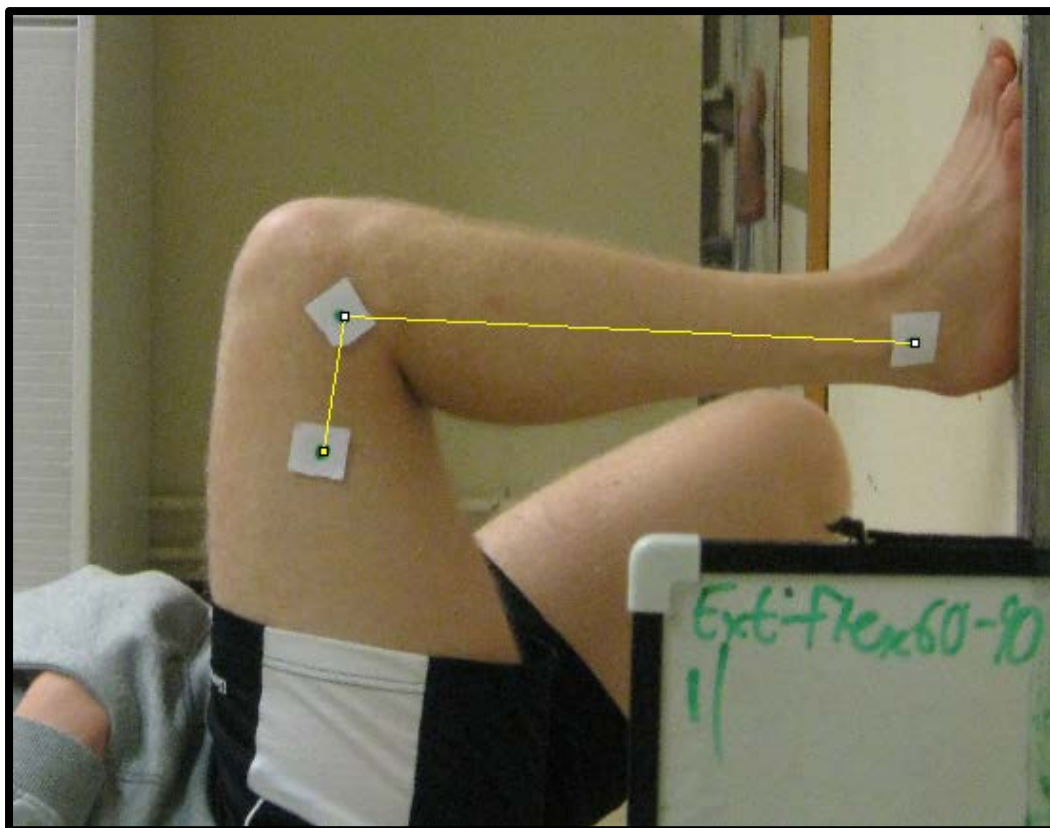
Figure 7. Typical set up and measurement of knee joint angle for active condition JPS measurement.

Data reduction

Knee angles were measured using open access two-dimensional manual digitizing software (ImageJ, U. S. National Institutes of Health,, Maryland, USA, http://imagej.nih.gov/ij/, 1997-

2012). Knee joint position sense was calculated from the average delta scores between target and reproduction angles across 15 trials, producing both real error scores (RES) in which magnitude and direction were measured and absolute error scores (AES) in which only magnitude was measured (Beynnon *et al*., 2000).

General reliability can be defined as the reproducibility or consistency of a measure (Atkinson and Nevill, 1998). Hopkins (2000) states test-retest reliability is one of the most important aspects of research, critical to the understanding of measurement error. The definition of test-retest reliability is concerned with the reproducibility of an individual's values across repeat data collection sessions (Hopkins, 2000). Test-retest reliability has been used to assess the reliability of lumbosacral position sense in the past (Brumagne *et al*., 1999). Test-retest reliability was assessed in the current study using intra-class correlation coefficients (specifically ICC, 3, 1; Weir, 2005) with 95% Confidence Intervals (CI), Standard Error Mean (SEM) (calculated as standard deviation x $\sqrt{1 - ICC}$), and Smallest Detectable Difference (SDD) (calculated as 1.96 x $\sqrt{2xSEM}$) (Batterham and George, 2000, Weir, 2005)). An ICC analysis was selected as the more traditional Pearson's product moment coefficients maybe biased towards small sample sizes (Hopkins, 2000) and has been discredited in previous work (Atkinson and Nevill, 1998). ICCs have the ability to differentiate among individuals and state the extent to which participants maintain their position in the sample across repeated trials (Batterham and George, 2000). The ICC model chosen in this study was ICC (3, 1), designated as a 2-way ANOVA mixed model for absolute agreement of a single measure to indicate the "relative reliability" (Batterham and George, 2000). SEM measures "real changes" in the context of measurement error, suggesting "absolute reliability" (Batterham and George, 2000). SDD is the minimum change required to be 95% confident that the change is real. Shrout and Fleiss (1979) state ICC results greater than 0.75 are excellent, between 0.40-0.75 are modest and less than 0.40 are poor.

Statistical analysis was completed using SPSS (Version 19, IBM Corporation, New York, USA). The Shapiro-Wilk test was used to examine normality of data, which was confirmed. Test-retest differences in scores and mean scores for all variables were correlated to examine for heteroscedasticity (Atkinson and Nevill, 1998). No significant correlation was found, indicating absence of heteroscedasticity, hence raw data was used for further analysis.

Results

Sitting Condition

Reliability analysis stated intra-class correlations coefficients ranged from 0.03-0.80 in RES data and 0.65-0.92 in AES data. ICCs, 95% confidence intervals, standard error of measurement and smallest detectable difference values are shown in tables six and seven. The results indicated that the most reliable test of knee JPS in the sitting condition may be from a starting angle of 0°, target angle through 60°-90°of flexion, using the dominant leg and AES variables.

Prone Condition

Reliability analysis stated interclass correlation coefficients ranged from 0.53-0.79 in RES data and 0.27-0.90 in AES data. ICCs, 95% confidence intervals, standard error of measurement and smallest detectable difference values are shown in tables eight and nine. The results indicated that the most reliable test of knee JPS in the prone condition may be from a starting angle of 0°, target angle through 30°-60°of flexion, using the dominant leg and AES variables.

Active Condition

Reliability analysis stated interclass correlation coefficients ranged from -0.18-0.89 in RES data and-0.13-0.82 in AES data. ICCs, 95% confidence intervals, standard error of measurement and smallest detectable difference values are shown in tables ten and 11. The results indicated that the most reliable test of knee JPS in the sitting condition may be from a starting angle of 90°, target angle through 10°-30°of extension, using the non-dominant leg and RES variables.

The test-retest reliability results indicate a large range of ICCs. The highest and hence "excellent" (Shrout and Fleiss, 1979) reliable measure of knee joint position sense was a sitting condition, dominant leg, from a starting angle of 0°, into flexion through 60°-90° of movement, calculating absolute error scores (ICC=0.92). The worst and hence measure of knee joint position sense with poor reliability was an active ("Total Trainer") condition, dominant leg, from a starting angle of 90°, into extension through 10°-30° of movement, calculating absolute error scores (ICC=-0.18). Furthermore, the active condition presented the poorest level of test-retest reliability, with only two out of 24 measures producing "excellent" (Shrout and Fleiss, 1979) test-retest reliability results. This maybe contradictory to the theory that suggests active-

active joint position sense measures may illicit better scores due to an increase of mechanoreceptor activity throughout the whole of the procedure, such as increased articular tissue strain in from adjacent joints (Fleming et al., 2001). However, this evidence may be true for fully weight-bearing tasks. The procedure in the current study required participants to lie supine and push off or lower towards a wall, not fully weight-bearing. This task was perhaps too abnormal for participants to become accustom to before data collection began.

Sitting Condition

Table 6. Mean (°), standard deviation (SD), intraclass correlation coefficient (ICC), 95% confidence intervals (CI), standard error of measurement (SEM) and smallest detectable difference (SDD) values for the Real Error Score (RES). [1]Session One Data; [2]Session Two Data; Fl – Ex = Knee flexion into knee extension, Ex-Fl = Knee extension into knee flexion.

Test	Mean[1]	SD[1]	Mean[2]	SD[2]	ICC	95% CI		SEM	SDD
Dominant Leg									
Fl – Ex 10°-30°	2.0	1.20	2.4	1.18	0.54	-0.08	0.86	0.82	2.26
Fl – Ex 30°-60°	2.0	1.83	1.5	2.25	0.78	0.36	0.94	0.96	2.65
Fl – Ex 60°-90°	-0.1	1.50	-0.3	2.06	0.80	0.38	0.95	0.83	2.31
Ex – Fl 10°-30°	-0.8	1.88	-1.2	1.27	0.03	-0.65	0.63	1.58	4.38
Ex – Fl 30°-60°	-1.0	1.83	-2.0	1.91	0.67	0.09	0.91	0.94	2.59
Ex – Fl 60°-90°	-1.7	1.53	-0.8	2.20	0.40	-0.20	0.80	1.45	4.02
Non-dominant Leg									
Fl – Ex 10°-30°	2.4	1.77	2.1	2.24	0.75	0.27	0.93	1.04	2.87
Fl – Ex 30°-60°	1.9	1.64	1.2	2.09	0.66	0.15	0.90	1.05	2.91
Fl – Ex 60°-90°	0	1.46	0	1.72	0.51	-0.18	0.86	1.14	3.17
Ex – Fl 10°-30°	-0.2	1.83	-0.8	1.57	0.62	0.08	0.89	1.01	2.81
Ex – Fl 30°-60°	-2.1	3.11	-2.1	1.79	0.58	-0.07	0.88	1.68	4.66
Ex – Fl 60°-90°	0.2	2.72	-0.9	2.00	0.30	-0.31	0.76	1.98	5.48

Table 7. Mean (°), standard deviation (SD), intraclass correlation coefficient (ICC), 95% confidence intervals (CI), standard error of measurement (SEM), and smallest detectable difference (SDD) values for the Absolute Error Score (AES). [1]Session One Data; [2]Session Two Data; Fl – Ex = Knee flexion into knee extension, Ex-Fl = Knee extension into knee flexion.

Test	Mean[1]	SD[1]	Mean[2]	SD[2]	ICC	95% CI		SEM	SDD
Dominant Leg									
Fl – Ex 10°-30°	2.5	1.09	2.5	1.06	0.76	0.26	0.93	0.55	1.53
Fl – Ex 30°-60°	2.6	1.49	2.4	1.63	0.86	0.54	0.96	0.60	1.67
Fl – Ex 60°-90°	1.7	0.89	2.1	0.98	0.70	0.20	0.91	0.49	1.35
Ex – Fl 10°-30°	2.3	1.05	2.4	0.97	0.79	0.37	0.94	0.47	1.31
Ex – Fl 30°-60°	3.1	1.27	3.3	1.00	0.86	0.54	0.96	0.44	1.23
Ex – Fl 60°-90°	3.2	1.40	3.3	1.35	0.92	0.72	0.98	0.40	1.10
Non-dominant Leg									
Fl – Ex 10°-30°	2.9	1.45	2.8	1.84	0.73	0.22	0.93	0.88	2.45
Fl – Ex 30°-60°	2.4	1.27	2.4	1.34	0.87	0.55	0.97	0.50	1.38
Fl – Ex 60°-90°	1.9	0.82	2.0	1.27	0.76	0.31	0.76	0.53	1.47
Ex – Fl 10°-30°	2.2	0.64	2.2	1.04	0.65	0.05	0.90	0.52	1.45
Ex – Fl 30°-60°	4.0	1.80	3.6	1.54	0.79	0.38	0.94	0.75	2.09
Ex – Fl 60°-90°	3.8	1.89	3.5	2.08	0.84	0.50	0.96	0.80	2.23

Prone Condition

Table 8. Mean (°), standard deviation (SD), intraclass correlation coefficient (ICC), 95% confidence intervals (CI), standard error of measurement (SEM), smallest detectable difference (SDD) values for the Real Error Score (RES). [1]Session One Data; [2]Session Two Data; Fl – Ex = Knee flexion into knee extension, Ex-Fl = Knee extension into knee flexion.

Test	Mean[1]	SD[1]	Mean[2]	SD[2]	ICC	95% CI		SEM	SDD
Dominant Leg									
Fl – Ex 10°-30°	2.0	2.16	2.5	2.96	0.75	0.26	0.93	1.31	3.62
Fl – Ex 30°-60°	0.9	3.19	1.4	2.07	0.54	-0.09	0.86	1.82	5.05
Fl – Ex 60°-90°	0.4	1.55	0.6	1.69	0.53	-0.10	0.86	1.11	3.08
Ex – Fl 10°-30°	-0.7	1.34	-1.2	1.34	0.67	0.12	0.91	0.77	2.13
Ex – Fl 30°-60°	-2.6	3.74	-2.3	3.03	0.69	0.15	0.91	1.90	5.28
Ex – Fl 60°-90°	-1.6	1.74	-2.3	1.67	0.68	0.12	0.91	0.97	2.69
Non-dominant Leg									
Fl – Ex 10°-30°	2.1	2.7	1.3	2.45	0.74	0.24	0.93	1.33	3.68
Fl – Ex 30°-60°	1.4	2.61	0.6	2.04	0.61	0.02	0.89	1.45	4.03
Fl – Ex 60°-90°	-0.2	1.51	-0.4	1.94	0.74	0.24	0.93	0.89	2.48
Ex – Fl 10°-30°	-1.5	1.50	-2.0	2.15	0.79	0.35	0.94	0.85	2.37
Ex – Fl 30°-60°	-2.4	4.20	-1.7	5.61	0.60	-0.01	0.88	3.14	8.71
Ex – Fl 60°-90°	-2.1	3.08	-1.8	3.03	0.58	-0.04	0.88	1.98	5.50

Table 9. Mean (°), standard deviation (SD), intraclass correlation coefficient (ICC), 95% confidence intervals (CI), standard error of measurement (SEM), smallest detectable difference (SDD) values for the Real Error Score (RES). [1]Session One Data; [2]Session Two Data; Fl – Ex = Knee flexion into knee extension, Ex-Fl = Knee extension into knee flexion.

Test	Mean[1]	SD[1]	Mean[2]	SD[2]	ICC	95% CI		SEM	SDD
Dominant Leg									
Fl – Ex 10°-30°	3.0	1.54	4.1	1.86	0.75	0.27	0.93	0.86	2.37
Fl – Ex 30°-60°	3.4	2.10	3.5	1.56	0.74	0.26	0.93	0.94	2.60
Fl – Ex 60°-90°	2.0	0.83	2.0	0.86	0.44	-0.23	0.82	0.64	1.76
Ex – Fl 10°-30°	1.9	0.84	2.1	1.71	0.27	-0.40	0.75	1.15	3.20
Ex – Fl 30°-60°	5.0	2.35	4.5	2.03	0.87	0.56	0.97	0.79	2.19
Ex – Fl 60°-90°	3.7	1.53	3.8	1.38	0.61	0.01	0.89	0.91	2.53
Non-dominant Leg									
Fl – Ex 10°-30°	4.0	1.85	3.0	1.57	0.67	0.11	0.91	0.99	2.75
Fl – Ex 30°-60°	3.9	1.88	3.2	1.65	0.82	0.42	0.95	0.76	2.10
Fl – Ex 60°-90°	2.2	1.39	2.3	1.37	0.71	0.19	0.92	0.75	2.07
Ex – Fl 10°-30°	2.7	1.64	2.9	1.91	0.85	0.51	0.96	0.69	1.90
Ex – Fl 30°-60°	5.1	2.52	6.0	4.23	0.25	-0.42	0.74	3.02	8.37
Ex – Fl 60°-90°	5.2	2.02	4.7	1.77	0.90	0.66	0.98	0.59	1.65

Active Condition

Table 10. Mean (°), standard deviation (SD), intraclass correlation coefficient (ICC) 95% confidence intervals (CI), standard error of measurement (SEM), and smallest detectable difference (SDD) values for the Real Error Score (RES). [1]Session One Data; [2]Session Two Data; Fl – Ex = Knee flexion into knee extension, Ex-Fl = Knee extension into knee flexion.

Test	Mean[1]	SD[1]	Mean[2]	SD[2]	ICC	95% CI		SEM	SDD
Dominant Leg									
Fl – Ex 10°-30°	3.0	1.54	4.1	1.86	0.75	0.27	0.93	0.86	2.37
Fl – Ex 30°-60°	3.4	2.10	3.5	1.56	0.74	0.26	0.93	0.94	2.60
Fl – Ex 60°-90°	2.0	0.83	2.0	0.86	0.44	-0.23	0.82	0.64	1.76
Ex – Fl 10°-30°	1.9	0.84	2.1	1.71	0.27	-0.40	0.75	1.15	3.20
Ex – Fl 30°-60°	5.0	2.35	4.5	2.03	0.87	0.56	0.97	0.79	2.19
Ex – Fl 60°-90°	3.7	1.53	3.8	1.38	0.61	0.01	0.89	0.91	2.53
Non-dominant Leg									
Fl – Ex 10°-30°	4.0	1.85	3.0	1.57	0.67	0.11	0.91	0.99	2.75
Fl – Ex 30°-60°	3.9	1.88	3.2	1.65	0.82	0.42	0.95	0.76	2.10
Fl – Ex 60°-90°	2.2	1.39	2.3	1.37	0.71	0.19	0.92	0.75	2.07
Ex – Fl 10°-30°	2.7	1.64	2.9	1.91	0.85	0.51	0.96	0.69	1.90
Ex – Fl 30°-60°	5.1	2.52	6.0	4.23	0.25	-0.42	0.74	3.02	8.37
Ex – Fl 60°-90°	5.2	2.02	4.7	1.77	0.90	0.66	0.98	0.59	1.65

Table 11. Mean, standard deviation (SD), intraclass correlation coefficient (ICC), 95% confidence intervals (CI), standard error of measurement (SEM), smallest detectable difference (SDD) values for the Absolute Error Score (AES). [1]Session One Data; [2]Session Two Data; Fl – Ex = Knee flexion into knee extension, Ex-Fl = Knee extension into knee flexion.

Test	Mean[1]	SD[1]	Mean[2]	SD[2]	ICC	95% CI		SEM	SDD
Dominant Leg									
Fl – Ex 10°-30°	1.8	0.52	1.6	0.49	-0.13	-0.68	0.51	0.54	1.49
Fl – Ex 30°-60°	3.0	1.49	3.0	1.02	0.41	-0.25	0.81	0.98	2.72
Fl – Ex 60°-90°	3.8	1.01	3.3	0.89	0.06	-0.56	0.64	0.92	2.56
Ex – Fl 10°-30°	3.2	1.27	2.3	0.84	0.42	-0.25	0.81	0.82	2.28
Ex – Fl 30°-60°	2.5	1.01	2.6	1.24	0.00	-0.60	0.60	1.13	3.14
Ex – Fl 60°-90°	1.7	0.58	1.8	0.62	-0.20	-0.72	0.46	0.66	1.83
Non-dominant Leg									
Fl – Ex 10°-30°	1.7	0.79	1.5	0.72	0.66	0.09	0.90	0.44	1.23
Fl – Ex 30°-60°	2.9	1.23	3.0	1.00	0.67	0.11	0.91	0.64	1.78
Fl – Ex 60°-90°	3.5	1.15	3.0	0.88	0.54	-0.09	0.86	0.69	1.92
Ex – Fl 10°-30°	2.8	1.05	3.0	1.15	0.82	0.42	0.95	0.47	1.31
Ex – Fl 30°-60°	2.7	0.52	3.0	1.10	0.22	-0.44	0.72	0.76	2.11
Ex – Fl 60°-90°	1.7	0.51	1.9	0.84	0.17	-0.48	0.70	0.63	1.76

3.2 Intra-Rater and Inter-Rater Reliability

Intra-rater and inter-rater reliability was confirmed using intra-class correlation coefficients (ICC 2, 1), 95% Confidence Intervals and Cronbach's Alpha (Field, 2005, Hopkins, 2000). Statistical analysis was completed in SPSS (Version 19, IBM Corporation, New York, USA). A randomly selected data set of 30 trials was analysed by the researcher and then by an independent rehabilitation practitioner; the ICC value between the two analyses was 0.98 and 95% confidence intervals ranged from 0.96-0.99. The Cronbach's Alpha value was 0.99. The researcher repeated the analysis of the randomly selected data set of 30 trials; the ICC value within the researcher was 0.96 and 95% confidence intervals ranged from 0.91-0.98. The Cronbach's Alpha value was 0.98. Therefore it can be confirmed that the intra-rater and inter-rater reliability of the analysis technique was at an acceptable level (Field, 2005, Shrout and Fleiss, 1979).

3.3 Learning Effect Analysis to Determine the Required Number of Trials for Clinical Knee Joint Position Sense Measurement in Three Conditions.

Introduction

Previous research has suggested between four and six trials are necessary for valid JPS measurement (Selfe *et al*., 2006). However, this research was conducted using an IKD and so the number of trials required using a clinical JPS measurement is unknown. The average of the first, middle and last five trials were calculated, following a similar method to Beynnon *et al*., (2000). Repeated measure ANOVAs were utilised to investigate the learning affect in all three JPS conditions (sitting, prone and active).

Data Reduction

Repeated Measures ANOVAs with three levels (Trials 1-5, 6-10 and 11-15) were used on each measure with "excellent" reliability (ICC>0.75, Shrout and Fleiss, 1979). This equated to 36 variables (see tables five to ten for details). Due to multiple ANOVAs, a bonferroni adjustment was made (Field, 2005) to the acceptable alpha level. The alpha level was reduced from 0.05 to 0.001 (0.05 / 36). All statistical analysis was completed in SPSS (Version 19, IBM Corporation, New York, USA).

Results

All JPS measures, except JPS measurements in the prone condition, non-dominant leg, into 60°-90° of extension using absolute error scores, reported no significant differences between 1-5, 6-10 and 11-15 trials (p>0.001). The single prone condition was significantly different between trials 1-5 and 6-10 only, so it may be concluded that for this measure, ten trials may be necessary. However it is suggested that five trials are adequate for all other JPS measurements with "excellent" reliability.

3.4 The Consistency, Sensitivity and hence "Optimum Condition" for Clinical Knee Joint Position Sense Measurement – The Effects of Condition, Leg, Direction and Target Angle.

Introduction

This analysis identified the effects of the following variables; error score (relative or absolute), condition (sitting, prone, active), leg (dominant or non-dominant), direction (flexion or extension) and range of motion (10°-30°, 30°-60° or 60°-90°) on JPS measurement. Hence, this analysis aimed to identify the optimal environment to collect consistent and sensitive knee joint position sense measurements. Previous research has identified poor correlation between different measures of knee proprioception (Grob *et al*., 2002, Kiran *et al*., 2010). It is therefore imperative practitioners use one consistent JPS measurement technique in rehabilitation and other clinical settings.

Data Reduction

Statistical analysis was completed in SPSS (Version 19, IBM Corporation, New York, USA). The effect of absolute or relative error scores, leg and direction of movement on JPS measurements was analysed using paired sample t-tests. Effect sizes were also calculated using the following equation –

$$r = \sqrt{\frac{t^2}{t^2 + df}}$$ (Field, 2005, p.294)

where *t* is the *t* statistic and *df* is the degrees of freedom.

The effect of range of motion and condition was analysed using one-way repeated measure ANOVAs. Effect sizes were also calculated using the following equation –

$$\omega^2 = \frac{[\frac{k-1}{nk}(MS_M - MS_R)]}{MS_R + \frac{MS_{BG} - MS_R}{k} + [\frac{k-1}{nk}(MS_M - MS_R)]}$$ (Field, 2005, p.452)

where *k* is the number of conditions, *n* is the sample size, MS_M is the mean square for the model, MS_R is the residual mean square and MS_{BG} is the mean square between groups.

All alpha levels were accepted at $p<0.05$. Effect sizes were interpreted using Cohen's (1992) classifications as follows; 0 – 0.1 is a small effect, 0.1-0.3 is a small to medium effect, 0.3-0.5 is a medium to large effect and 0.5 and above is a large effect.

Results

Results of the statistical analysis are shown in Table 12. Absolute and relative error scores differ which was expected and as such data were kept separate. Leg dominance had a main effect on relative error scores ($p=0.005$, $r=0.78$) but not absolute error scores ($p>0.05$). Therefore data were pooled for AES data only. Range of motion had an effect on relative error scores ($p= 0.032$, $\omega^2=19$) but the effect size was small. Absolute error scores were not affected by range of motion ($p>0.05$). The direction of knee motion (flexion / extension) had an effect on relative and absolute error scores; $p=0.02$, $r=0.81$ and $p=0.009$, $r=0.74$ respectively. Condition (sitting, prone, active) was also a main effect for both relative ($p=0.036$, $\omega^2=0.21$) and absolute ($p=0.001$, $\omega^2=0.37$) error scores although effects sizes were small.

Table 12. Statistical analyses on the effects of relative or absolute error scores, leg, range of motion, direction and condition on knee JPS measurements.

VARIABLE	JPS(°) Mean±SD	TEST	RESULTS	
RES AES	0.3±0.60 3.0±0.97	Paired t-test	p=0.0001, $r = 0.97$	Absolute and Relative Scores Differ.
RES Dominant (D) RES Non-Dominant (ND) AES Dominant (D) AES Non-Dominant (ND)	-0.3±0.83 1.1±0.82 3.0±1.12 3.0±0.90	2 x Paired t-test	RES p=0.005, $r = 0.78$ AES p=0.728, $r = 0.12$	Leg choice affects RES scores but not AES scores.
RES D Low-Range RES D Mid-Range RES D High-Range RES ND Low-Range RES ND Mid-Range RES ND High-Range AES Low-Range AES Mid-Range AES High-Range	0.7±1.14 -0.5±1.07 0.9±1.18 1.0±1.09 1.9±1.64 0.6±1.62 2.7±0.84 3.4±1.35 3.0±1.03	3 x One Way ANOVA	RES D p=0.032 $\omega^2 = 0.19$ RES ND p=0.207 $\omega^2 = 0.06$ AES p=0.089 $\omega^2 = 0.05$	Range affects RES Dominant Leg, but not RES Non-dominant Leg or AES measures.
RES Flexion RES Extension AES Flexion AES Extension	1.5±1.12 -1.5±1.41 2.7±1.05 3.4±1.00	2 x Paired t-test	RES p=0.02, $r = 0.81$ AES p=0.009, $r = 0.74$	Direction affects both RES and AES.
RES Sitting RES Prone RES Active AES Sitting AES Prone AES Active	1.0±0.97 -0.3±1.03 0.9±1.03 2.7±0.84 3.7±1.43 2.3±0.92	2 x One Way ANOVA	RES p=0.036 $\omega^2 = 0.21$ AES p=0.001 $\omega^2 = 0.37$	Condition affects both RES and AES.

Summary

In summary knee joint position sense measurements are more consistent and less variable using absolute error scores. Relative error scores were affected by leg dominance, range of motion, direction and condition. If practitioners were to select relative error score as a measurement in clinical practice this study would recommend data be collected from both legs, across low, medium and high ranges of motion, in both directions. This would have obvious time

implications in practice. Therefore, it is recommended absolute error scores be used in future clinical measurements. The flow chart below explains each choice a practitioner should make when measuring clinical joint position sense.

3.5 Flow Chart to Illustrate the Decision Making Process to Ascertain the Optimum JPS Measurement Technique.

The flow diagram below demonstrates the decisions made to ascertain the optimum conditions for knee joint position sense techniques. Each question is answered using the results of the previous studies. The diagram also demonstrates the number of issues practitioners would need to consider during clinical assessment of joint position sense.

72 dependant JPS variables including combinations of independent variables - legs, three conditions (sitting, prone and active), three ROMs (small, medium, large) and two directions (flexion and extension).

Research Question 1: Which variables are reliable over time?

Test – Re-Test Reliability Analysis

36 Dependant Variables with ICCs over 0.7[1].

36 Dependant Variables with ICCs below 0.7 and discarded.

Research Question 2: How many trials are needed to achieve a consistent JPS score?

Trial Analysis/ Learning Effect

One Way Repeated Measures ANOVAs revealed no significant differences between the average scores from the first (1-5), middle (6-10) and last (11-15) trials for all except one (prone condition, left leg, 60°-90° of extension) of the 36 variables. This suggests the first five scores are no different from the middle or last five scores. Hence, five trials are deemed sufficient for most JPS measurement.

Research Question 3: Are there differences between RES and AES Scores?

Types of Error Score (RES and AES)

Paired t-test revealed significant difference between RES and AES (p=0.0001). RES had a lower error score, but as direction was considered is expected.
RES and AES produce different JPS scores and must be kept separate.

Research Question 4: Are there differences in JPS Scores between dominant and non-dominant legs?

Legs (Dominant and Non-dominant).

Paired t-tests revealed a significant difference in error scores between legs for RES (P=0.005) but not AES (P=0.728). Hence, dominant and non-dominant legs produce different relative error scores but not absolute error scores. If RES is used both legs must be measured, but only one leg can be measured if AES is used.

Research Question 5: Does the range of motion (ROM) in JPS measurement affect scores?

Ranges of Motion - Low (10°-30°), Medium (30°-60°) and High (60°-90°).

One-way Repeated Measure ANOVAs compared error scores between low, middle and high ROMs.

RES –Significant differences in scores for dominant leg (p=0.032), but not non-dominant leg (P=0.207). Therefore ROM affects RES. At this stage RES was discarded as a JPS variable[2].

AES – No significant differences in scores (p=0.089). Hence, ROM does not affect AES; any range can be used in JPS measurement.

Research Question 6: Does the direction in JPS measurement affect scores?

Directions - Flexion and Extension

AES - Paired t-tests revealed a significant difference in error scores between flexion and extension directions (p=0.009).Hence direction does affect error scores and both directions must be used in JPS measurement.

Research Question 7: Does the condition in JPS measurement affect scores?

Conditions - Sitting, Prone and Active

One-way Repeated Measure ANOVAs compared error scores between sitting, prone and active conditions.

Significant differences were found between all conditions (p=0.001).

Prone had the highest mean error score and was discarded. Sitting and active had comparable error scores (difference of 0.2°). Therefore ICCs were considered.

Sitting had more test-retest reliability (ICC>0.7) measures (12 out of 12) than active (1 out of 12). Therefore, active was discarded.

Research Question 8: What is the final JPS method?

FINAL METHOD

Five trials, absolute error scores, dominant leg (best score[3]), medium range of motion (30°-60°) for extension, high range of motion for flexion (60°-90°) (highest ICCs[4]), both directions (flexion and extension) in a sitting condition.

[1]Interclass correlation coefficients over 0.7 provide "good to excellent" measures of reliability (Shrout and Fleiss, 1979).

[2]At this stage, leg and range significantly affected RES. In order for RES methods to be consistent practitioners would need to take JPS from both legs and three ranges; this would not be possible in treatment settings. Therefore, RES was discarded.

[3]For consistency, dominant legs will be used for JPS measures. Also, the dominant leg produced the best error score.

3.6 The Construct Validity of Clinical Knee Joint Position Sense Measurement

Introduction

In general, validity can be defined as the credibility and accuracy of the measurement tool (George *et al*., 2000). Concurrent or criterion validity is the process by which a clinical measurement tool is compared to a previously validated or "gold standard" measurement tool. Previous studies on knee JPS used a variety of measuring equipment including 2D video analysis, IKDs and purpose built lever systems (Beynnon *et al*., 2000). However, no study has compared a reliable clinical test to the "gold standard" method for joint angle measurement (an IKD) and hence tested the concurrent validity of a reliable JPS measurement.

Participants

Ten healthy participants (five female; age 28.0±13.29 years, mass 60.3±9.02 kg, height 1.65±0.07 m, BMI 22.1±1.80, GPPAQ range Inactive – Active, Tegner 5.0±1.22, KOOS 98.6±3.18, Lysholm 98.8±2.68 and five male; 29.6±10.74 years, mass 73.6±5.86 kg, height 1.75±0.07 m, BMI 24.1±1.97, GPPAQ range Active, Tegner 7.8±1.30, KOOS 92.5±10.87, Lysholm 87.6±17.5) took part in the study and were recruited using a convenience sampling method. All were free from lower extremity injury and neurological disease. Participants read an information sheet and provided written informed consent (see appendix two and three). This study was approved by the university ethics board (Ref09/25).

Procedures

The study was a random cross-over design; hence participants were tested using both methods, a week apart. Participants wore shorts and removed their sock and shoe of their dominant leg. The participants were prepared for data collection by placing markers on the following anatomical points; a point on a line following the greater trochanter to the lateral epicondyle, close to the lateral epicondyle (placement of a marker directly on the greater trochanter is difficult due to clothing), the lateral epicondyle and the lateral malleolus of the dominant leg (following Andersen *et al*., 1995).

Clinical knee JPS measurements were collected using the protocol determined as the most reliable by the previous study. The researcher gave a brief explanation of the JPS protocol before data collection to ensure the participant felt comfortable being blindfolded during the testing. The participants were then seated on the end of a physiotherapy plinth and blindfolded.

The dominant leg was passively moved by the researcher through 30°-60° of knee extension from a starting knee angle of 90° or through 60°-90° of knee flexion from a starting angle of 0° to a target angle at an angular velocity of approximately 10°/s (Marks and Quinney, 1993). The order of the target angles was randomly allocated using randomly generated numbers. The participant then actively held the leg in this position for 5s. A photograph of the leg in the target position was taken (see figure four) using a standard camera (Casio Exilim, EX-FC100, Casio Electronics Co.,Ltd. London, UK) placed 3m from the sagittal plane of movement on a fixed level tripod (Camlink TP-2800,Camlink UK, Leicester, UK). The camera set up followed the British Association of Sport and Exercise Sciences (BASES) guidelines (Payton, 2008). The leg was then passively returned to the starting angle and the participant was instructed to actively move the same leg to the target angle and hold the leg in this position. Another photograph was taken and the participant instructed to move their leg back to the starting position. The process was repeated 5 times for each target angle on the dominant leg.

Knee JPS measurements were also collected using an IKD (Humac Norm 776, CSMi, Massachusetts, USA). A specific protocol was written to ensure the IKD passively moved the participant's dominant leg to the pre-determined target angles, therefore removing any researcher bias. Details of this protocol can be found in appendix four. Participants wore shorts and removed their sock and shoe from their dominant leg. The participant was then seated in the IKD chair, however, was not secured in to the chair as this may have introduced sensory feedback from the popliteal fossa, which was not present in the clinical trials. Once the centre of rotation of the dominant knee had been correctly aligned to the centre of rotation of the IKD lever axis, the leg was strapped to the lever and the participant blindfolded. The IKD protocol then passively moved the leg through 30°-60° of extension from a starting knee angle of 90° or through 60°-90° of flexion from a starting angle of 0° to a specified target angle at an angular velocity of 2°/s (Beynnon *et al*. 2000). Target angles were randomly selected across the range of motion (see appendix four). The leg was held in this position for 5s then returned to the starting angle. The participant was then instructed to move their leg to the target angle and hold, at which point the experimenter noted the knee angle using the IKD software. This process was repeated 5 times for both knee extension and flexion.

Data Reduction

Knee angles from the clinical JPS testing were measured using two-dimensional manual digitizing software from the image capture data (ImageJ, U. S. National Institutes of Health,, Maryland, USA, http://imagej.nih.gov/ij/, 1997). Knee joint position sense was calculated from the average delta scores between target and reproduction angles across five flexion and five extension trials producing absolute error scores (Beynnon *et al.*, 2000) Absolute error scores from IKD data were calculated by subtracting the reproduction angle from the target angle set in the protocol. The average of the five extension trials and five flexion trials were used for further analysis in each condition (clinical and IKD).

All statistical analysis was completed in SPSS (Version 19, IBM Corporation, New York, USA). The Shapiro-Wilk test was used to examine normality of data, which was confirmed. Related samples t-tests were used to compare clinical and IKD absolute error scores. Pearson Correlation Coefficients were used to examine the relationship between clinical and IKD JPS AES. An alpha level was set at $p<0.05$. Significant relationships were defined using Cohen's definitions; r=.10 (small relationship), r=.30 (medium relationship), r=.50 (large relationship) (Cohen, 1992).

Results

There was no significant difference between clinical AES ($3.7°\pm1.40$) and IKD AES ($4.3°\pm1.83$) knee flexion data ($p= 0.263$). There was also no significant relationship between these two variables ($p=0.185$, $r=0.457$). There was a significant difference between clinical AES ($2.5°\pm0.72$) and IKD AES ($4.3°\pm1.90$) knee extension data ($p=0.016$). The relationship between these two variables although large, was not significant ($p= 0.740$, $r=0.120$).

These results suggest that clinical JPS measurements using knee flexion are valid against a gold standard knee angle positioning tool. However, JPS measurements using knee extension may not provide concurrent validity.

3.7 Normative Knee Joint Position Sense Based on a UK Adult Population.

Introduction

Current research does not provide normative levels of joint position sense. Callaghan *et al.*, (2002) suggests "good" levels of knee proprioception to be below an absolute mean error score of 5°, however this figure appears arbitrary. No large scale JPS data exists on a knee injury population using a reliable measurement technique.

Participants

A sample size calculation was utilised to provide an appropriate sample size producing 90% power and alpha set at 0.05. The sample size was calculated in statistical software (G*Power, version 3.1.6, Germany) (Field, 2005) using data from the previous meta-analysis (Relph *et al.*, 2014) on ACL injuries and JPS (see chapter 2). Using the independent t-test method, the effect size was calculated using the mean JPS scores and accompanying standard deviations from the fixed-effect meta-analysis data (Relph *et al.*, 2014). Although this method is not ideal, previous JPS data were not available on a large-scale uninjured sample. The calculated sample size was 104.

The 104 sample size was then divided into appropriate age groups, based on UK population statistics (National Population Projections, 2010-based reference volume: Series PP2, Office of National Statistics). This resulted in a target of 24 participants aged 15-29, 24 participants aged 30-44, 24 participants aged 45-59, 20 participants aged 60-74 and 12 participants aged 75 and over. The participants were recruited using convenience but purposive sampling techniques. Table 13 details the sample. There were some initial difficulties recruiting participants over 60 due to the nature of the test, particularly the knee flexion test which requires adequate muscular strength to hold the leg unaided at 0° (full extension). However, the final sample size was 116 as more participants volunteered than expected.

All participants were free from lower extremity injury and neurological disease. Participants completed four self-assessment surveys including; the Tegner Activity Survey, the General Practitioner Physical Activity Questionnaire, the Knee injury and Osteoarthritis Outcome Score (KOOS) and the Lysholm Knee Scale. Participants read an information sheet and provided written informed consent (see appendix two and three). This study was approved by the university ethics board (Ref09/25).

Table 13. Participant details of study 3.7.

Age Group (years)	Gender Split	Age (mean ±SD years)	Mass (mean±SD kg)	Height (mean±SD m)	BMI (mean ±SD)	KOOS (mean±SD)	Lysholm Score (mean±SD)	Tegner Score (mean±SD)	GPPAQ Score (range)
15-29	Males = 13	22±4.3	74.2±7.33	1.79±0.061	23.1±2.01	97.9±4.08	95±8.03	7.2±1.01	Active
	Females = 16	22±3.4	65.1±11.86	1.65±0.058	23.9±3.60	99.6±1.78	99.7±1.25	5.4±1.59	Inactive - Active
30-44	Males = 13	37±4.8	84.3±14.39	1.79±0.081	26.2±3.28	92.2±18.54	94.92±10.45	5.2±2.12	Moderately Inactive - Active
	Females =12	39±3.5	70.8±16.24	1.65±0.084	25.7±4.22	94.9±10.15	93.7±11.81	4.5±1.93	Inactive-Active
45-59	Males = 12	53±3.1	76.4±11.46	1.78±0.06	24.1±3.20	96.6±6.05	96.9±7.28	4.0±1.54	Inactive - Active
	Females = 13	52±4.8	65.4±14.70	1.64±0.049	24.3±6.15	90.7±14.49	90.6±13.50	4.2±1.68	Inactive - Active
60-74	Males = 11	68±4.6	90.4±12.7	1.77±0.044	29.0±3.98	90.8±21.80	90.6±17.04	2.4±0.67	Inactive – Active
	Females = 15	64±3.2	75.1±26.00	1.60±0.090	29.4±10.49	92.5±13.53	91.3±12.23	2.6±0.63	Inactive – Active
>74	Males = 5	76±1.2	84.8±15.51	1.73±0.132	28.9±8.54	80.4±20.50	77.4±20.77	2.2±1.30	Inactive – Active
	Females = 6	77±3.1	70.8±16.47	1.59±0.067	28.1±5.68	92.5±9.87	89.3±17.05	2.2±0.98	Inactive – Moderately Inactive

Procedures

Participants wore shorts and removed the sock and shoe from their dominant leg. The participants were prepared for data collection by placing markers on the following anatomical points; a point on a line following the greater trochanter to the lateral epicondyle, close to the lateral epicondyle (placement of a marker directly on the greater trochanter is difficult due to clothing), the lateral epicondyle and the lateral malleolus of both legs (following Andersen *et al*., 1995).

Clinical knee JPS measurements were collected using the protocol determined as the most reliable by the previous study. The researcher gave a brief explanation of the JPS protocol before data collection to ensure the participant felt comfortable being blindfolded during the testing. The participant was then seated on the end of a physiotherapy plinth and blindfolded. The dominant leg was passively moved by the experimenter through 30°-60° of extension from a starting knee angle of 90° or through 60°-90° of flexion from a starting angle of 0° to a target angle at an angular velocity of 10°/s (Marks and Quinney, 1993). The order of the target angles was randomly allocated using randomly generated numbers. The participant then actively held the leg in this position for 5s. A photograph of the leg in the target position was taken using a standard camera (Casio Exilim, EX-FC100, Casio Electronics Co.,Ltd. London, UK) placed 3m from the sagittal plane of movement on a fixed level tripod (Camlink TP-2800,Camlink UK, Leicester, UK). The camera set up followed the British Association of Sport and Exercise Sciences (BASES) guidelines (Payton, 2008). The leg was then passively returned to the starting angle and the participant was instructed to actively move the same leg to the target angle and hold the leg in this position. Another photograph was taken and the participant instructed to move their leg back to the starting position. The process was repeated 5 times for each target angle on the dominant leg.

Data Reduction

Knee angles were measured using two-dimensional manual digitizing software (ImageJ, U. S. National Institutes of Health,, Maryland, USA, http://imagej.nih.gov/ij/, 1997-2012). Knee joint position sense was calculated from the average delta scores between target and reproduction angles across five flexion and five extension trials producing absolute error scores in which only magnitude was measured (Beynnon *et al*., 2000). Means, standard deviations and 95% confidence intervals were presented where appropriate. Confidence intervals are provided to indicate the true boundaries in which a mean would fail, in this case, the 95%

boundary (Field, 2005). Confidence intervals present the results using the same data measurement as the mean and as such, can improve the clarity of true meaning of the sample data (Gardner and Altman, 1986). Confidence intervals at the 95% level were calculated using the following equation –

Lower boundary of confidence interval $= \bar{X} - (1.96 \ X \ SE)$

Upper boundary of confidence interval $= \bar{X} + (1.96 \ X \ SE)$

(Gardner and Altman, 1986, p. 748)

All statistical analysis was completed in SPSS (Version 19, IBM Corporation, New York, USA). The Kolmogorov-Smirnov test was used to examine normality of data, which was confirmed. Significant differences between JPS flexion and extension absolute error scores were tested using a dependent t-test with an alpha level set at $p < 0.05$. The effect of age group (15-29 years, 30-44 years, 45-59 years, 60-74 years, >74years), gender and GPPAQ score (active, moderately active, moderately inactive and inactive) on JPS flexion and extension absolute error scores was tested using a multivariate general linear model (MANOVA, Field, 2005) with an alpha level set at $p < 0.05$. Significant correlations between JPS flexion and extension absolute error scores and age, mass, height, BMI, Tegner, Lysholm and KOOS scores were analysed using Pearson Product Correlation Coefficients for interval level data and Spearman's Rank Correlation Coefficients for ordinal level data (Field, 2005) and alpha levels set at $p < 0.05$. Significant relationships were defined using Cohen's definitions; $r = .10$ (small relationship), $r = .30$ (medium relationship), $r = .50$ (large relationship) (Cohen, 1992).

3.8 Anterior Cruciate Ligament Deficient Knee Joint Position Sense in a Non-Athletic Population.

Introduction

Previous research has stated that ACL injuries may significantly reduce knee joint position sense (see meta-analysis appendix 1a and chapter 2). However, the reliability of JPS measurement techniques has not been well reported. Therefore, this study compared an ACL deficient population to an uninjured population using a JPS measurement previously tested for reliability.

Participants

Twenty ACL deficient (ten male, ten female, age 30±4.5years, mass 77.4±4.76kg, height 1.63±0.24m, Tegner 5.5±1.2, Lysholm 76±9.8, time since injury 11±2 months) took part in the study, recruited using purposive sampling methods. Diagnosis of their injury was confirmed by clinical laxity testing (anterior drawer test, Lachman's test and pivot shift test), and further verified by either arthroscopic or Magnetic Resonance Image (MRI) examination. All patients suffered the injury through non-contact means and none of the patients had concurrent medial collateral ligament or meniscal injuries at the time of the ACL injury. Participants read an information sheet and provided written informed consent (see appendix two and three). This study was approved by the university ethics board (REP10/068)

The data from 20 healthy participants matched to the ACL deficient participants by age, gender and physical activity (ten female; age 28.0±13.29 years, mass 60.3±9.02 kg, height 1.65±0.07 m, BMI 22.1±1.80, GPPAQ range Inactive – Active, Tegner 5.0±1.22, KOOS 98.6±3.18, Lysholm 98.8±2.68 and ten male; 29.6±10.74 years, mass 73.6±5.86 kg, height 1.75±0.07 m, BMI 24.1±1.97, GPPAQ range Active, Tegner 7.8±1.30, KOOS 92.5±10.87, Lysholm 87.6±17.5) were taken from the normative study (see section 3.7). The controls were matched in this way as previous literature has suggested knee JPS may be influenced by such variables (for more information see chapter 2). All were free from lower extremity injury and neurological disease.

Procedures

Participants wore shorts for data collection. Uninjured participants removed the shoe and sock from their dominant leg. ACL deficient participants removed both shoes and socks. Participants

were prepared for data collection by placing markers on the following anatomical points; a point on a line following the greater trochanter to the lateral epicondyle, close to the lateral epicondyle (placement of a marker directly on the greater trochanter is difficult due to clothing), the lateral epicondyle and the lateral malleolus of both legs for ACL deficient participants and dominant leg for uninjured participants (following Andersen *et al*., 1995).

Clinical knee JPS measurements were collected using the protocol determined as the most appropriate for comparison to an ACL deficient population. Both bundles of the ACL are taut in 10°-30° of flexion and hence have maximal mechanoreceptor activity in this range of motion. Therefore, testing JPS in this range may allow participants to produce their "maximum" performance of knee joint position sense. Furthermore, the previous study on reliability of JPS measurement confirmed knee joint position sense measurements using this technique provided "excellent" reliability statistics (ICC=0.79, Shrout and Fleiss, 1979).

The researcher gave a brief explanation of the JPS protocol before data collection to ensure the participant felt comfortable being blindfolded during the testing. The participants were then seated on the end of a physiotherapy plinth and blindfolded. The leg was passively moved by the experimenter through 10-30° of knee flexion from a starting angle of 0° to a target angle at an angular velocity of approximately 10°/s (Marks and Quinney, 1993). The participant then actively held the leg in this position for 5s. A photograph of the leg in the target position was taken using a standard camera (Casio Exilim, EX-FC100, Casio Electronics Co.,Ltd. London, UK) placed 3m from the sagittal plane of movement on a fixed level tripod (Camlink TP-2800,Camlink UK, Leicester, UK). The camera set up followed the British Association of Sport and Exercise Sciences (BASES) guidelines (Payton, 2008). The leg was then passively returned to the starting angle and the participant was instructed to actively move the same leg to the target angle and hold the leg in this position. Another photograph was taken and the participant instructed to move their leg back to the starting position. The process was repeated 5 times. The ACL deficient group completed the test using both legs. The uninjured group used their dominant leg only.

Data Reduction

Knee angles were measured using two-dimensional manual digitizing software (ImageJ, U. S. National Institutes of Health,, Maryland, USA, http://imagej.nih.gov/ij/, 1997-2012). Knee joint position sense was calculated from the average delta scores between target and reproduction angles across five flexion trials producing absolute error scores (AES) in which

only magnitude was measured (Beynnon *et al*., 2000). Means, standard deviations and 95% confidence intervals were presented. Confidence intervals are provided to indicate the true boundaries in which a mean would fail, in this case, the 95% boundary (Field, 2005). Confidence intervals present the results using the same data measurement as the mean and as such, can improve the clarity of true meaning of the sample data (Gardner and Altman, 1986). Confidence intervals at the 95% level were calculated using the following equation –

Lower boundary of confidence interval $= \bar{X} - (1.96 \; X \; SE)$

Upper boundary of confidence interval $= \bar{X} + (1.96 \; X \; SE)$

(Gardner and Altman, 1986, p. 748)

All statistical analysis was completed in SPSS (Version 19, IBM Corporation, New York, USA). The Shapiro-Wilk test was used to examine normality of data, which was not confirmed. Log transformation of data did not solve the issue of normality, hence non-parametric statistical analysis was utilised. A related samples Wilcoxon signed rank test compared differences between the ACL deficient leg and the contralateral leg. Independent sample Mann-Whitney U tests were used to compare the differences between ACL deficient legs and external controls, and contralateral legs of the ACL deficient participants and external controls. The level of acceptable significance was set a *p*<0.05.

3.9 Anterior Cruciate Ligament Reconstructed Knee Joint Position Sense in an Elite Athletic Population.

Participants

Ten elite athletes (three male, seven female; age 22.4±3.75 years; three taekwondo competitors, three footballers, two netballers, one middle distance runner, one judo competitor) who had all undergone ACL reconstructive surgery (17.9±4.68 months since surgery; type of reconstruction; six hamstring, 4 bone-patellar tendon bone) took part in the study and were recruited using purposive sampling. All had returned to playing elite level sport (6.2±0.63 months since return to play; Lysholm 94.2±1.69) at either a junior international (n=5) or senior international (n=5) level.

The data from 10 healthy participants taken from the large scale normative study (see section 3.7) (three male, seven female; age 22.1± 4.07years; Lysholm 100±0) acted as age, gender, physical activity and knee condition matched controls. The controls were matched in this way as previous literature has suggested knee JPS may be influenced by such variables (for more information see chapter 2). All were free from lower extremity injury and neurological disease. Participants read an information sheet and provided written informed consent (see appendix two and three). This study was approved by the university ethics board (REP10/068).

Procedures

Participants wore shorts and removed their socks and shoes. The participants were prepared for data collection by placing markers on the following anatomical points; a point on a line following the greater trochanter to the lateral epicondyle, close to the lateral epicondyle (placement of a marker directly on the greater trochanter is difficult due to clothing), the lateral epicondyle and the lateral malleolus of both legs (following Andersen *et al*., 1995).

Clinical knee JPS measurements were collected using the protocol determined as the most reliable by the previous study. The researcher gave a brief explanation of the JPS protocol before data collection to ensure the participant felt comfortable being blindfolded during the testing. The participant was then seated on the end of a physiotherapy plinth and blindfolded. The leg was passively moved by the experimenter through 30°-60° of extension from a starting knee angle of 90° or through 60°-90° of flexion from a starting angle of 0° to a target angle at an angular velocity of 10°/s (Marks and Quinney, 1993). The order of the target angles was

randomly allocated using randomly generated numbers. The participant then actively held the leg in this position for 5s. A photograph of the leg in the target position was taken using a standard camera (Casio Exilim, EX-FC100, Casio Electronics Co.,Ltd. London, UK) placed 3m from the sagittal plane of movement on a fixed level tripod (Camlink TP-2800,Camlink UK, Leicester, UK). The leg was then passively returned to the starting angle and the participant was instructed to actively move the same leg to the target angle and hold the leg in this position. Another photograph was taken and the participant instructed to move their leg back to the starting position. The process was repeated 5 times for each target angle on the injured and uninjured leg of the ACL group and the dominant leg of the control group.

Data Reduction

Knee angles were measured using two-dimensional manual digitizing software (ImageJ, U. S. National Institutes of Health,, Maryland, USA, http://imagej.nih.gov/ij/, 1997-2012). Knee joint position sense was calculated from the average delta scores between target and reproduction angles across five flexion and five extension trials producing absolute error scores in which only magnitude was measured (Beynnon *et al*., 2000). Means, standard deviations and 95% confidence intervals were presented. Confidence intervals are provided to indicate the true boundaries in which a mean would fail, in this case, the 95% boundary (Field, 2005). Confidence intervals present the results using the same data measurement as the mean and as such, can improve the clarity of true meaning of the sample data (Gardner and Altman, 1986). Confidence intervals at the 95% level were calculated using the following equation –

Lower boundary of confidence interval $= \bar{X} - (1.96\ X\ SE)$

Upper boundary of confidence interval $= \bar{X} + (1.96\ X\ SE)$

(Gardner and Altman, 1986, p. 748)

All statistical analysis was completed in SPSS (Version 19, IBM Corporation, New York, USA). The Kolmogorov-Smirnov test was used to examine normality of data, which was confirmed. Significant differences between the injured and uninjured legs of the ACL group were tested using a dependent t-test with an alpha level set at $p<0.05$. Significant difference between the injured or uninjured legs of the ACL group and the leg of the control group were tested using independent t-tests with an alpha level set at $p<0.05$. Effect sizes were also calculated using the following equation –

$$r = \sqrt{\frac{t^2}{t^2 + df}}$$ (Field, 2005, p.294)

where t is the t statistic and df is the degrees of freedom.

3.10 Knee Injuries other than Ligament Injuries and Knee Joint Position Sense.

Participants

Fifteen participants with knee injuries other than ACL damage (four male, eleven female, age 40.5±16.69 years, mass 80.8±26.44, height 1.7±0.09 m, BMI 28.3±10.88, GPPAQ range inactive – Active, Tegner 5.1±2.00, Lysholm 71.3±20.64, KOOS 75.4±18.81) took part in the study, recruited using a convenience sampling method during recruitment for the large scale normative study (see section 3.7). These injuries included three participants with patella re-alignments, two with patellofemoral pain syndrome, two with the early stages (grade 1) of osteoarthritis, three with a cartilage tear, one with regular knee sprains, one with hypermobility and two with tibia fractures and re-structuring. All diagnoses were completed by a health care professional, either a physiotherapist or medical consultant. All participants had completed a full programme of rehabilitation and had been discharged by the medical professional at least four months earlier.

The data from 15 healthy participants taken from the large scale normative study (see section 3.7) (four male, eleven female, age 40.6±17.06 years, mass 67.2±12.14 kg, height 1.7±.0.08 m, BMI 24.0±2.98, GPPAQ range Inactive – Active, Tegner 4.6±2.13, KOOS 99.2±2.22, Lysholm 99.1±2.58) acted age, gender, physical activity and knee condition matched controls. The controls were matched in this way as previous literature has suggested knee JPS may be influenced by such variables (for more information see chapter 2). All controls were free from lower extremity injury and neurological disease. Participants read an information sheet and provided written informed consent (see appendix two and three). This study was approved by the university ethics board (REP10/068).

Procedures

Participants wore shorts and removed the sock and shoe from their dominant or previously injured leg. The participants were prepared for data collection by placing markers on the following anatomical points; a point on a line following the greater trochanter to the lateral epicondyle, close to the lateral epicondyle (placement of a marker directly on the greater trochanter is difficult due to clothing), the lateral epicondyle and the lateral malleolus of both legs (following Andersen et al., 1995).

Clinical knee JPS measurements were collected using the protocol determined as the most reliable by the previous study. The researcher gave a brief explanation of the JPS protocol before data collection to ensure the participant felt comfortable being blindfolded during the testing. The participant was then seated on the end of a physiotherapy plinth and blindfolded. The dominant leg was passively moved by the experimenter through 30°-60° of extension from a starting knee angle of 90° or through 60°-90° of flexion from a starting angle of 0° to a target angle at an angular velocity of 10°/s (Marks and Quinney, 1993). The order of the target angles was randomly allocated using randomly generated numbers. The participant then actively held the leg in this position for 5s. A photograph of the leg in the target position was taken using a standard camera (Casio Exilim, EX-FC100, Casio Electronics Co.,Ltd. London, UK) placed 3m from the sagittal plane of movement on a fixed level tripod (Camlink TP-2800,Camlink UK, Leicester, UK). The leg was then passively returned to the starting angle and the participant was instructed to actively move the same leg to the target angle and hold the leg in this position. Another photograph was taken and the participant instructed to move their leg back to the starting position. The process was repeated five times for each target angle on the dominant or previously injured leg.

Data Reduction

Knee angles were measured using two-dimensional manual digitizing software (ImageJ, U. S. National Institutes of Health,, Maryland, USA, http://imagej.nih.gov/ij/, 1997-2012). Knee joint position sense was calculated from the average delta scores between target and reproduction angles across five flexion and five extension trials producing absolute error scores (AES) in which only magnitude was measured (Beynnon et al., 2000). Means, standard deviations and 95% confidence intervals were presented. Confidence intervals are provided to indicate the true boundaries in which a mean would fail, in this case, the 95% boundary (Field, 2005). Confidence intervals present the results using the same data measurement as the mean and as such, can improve the clarity of true meaning of the sample data (Gardner and Altman, 1986). Confidence intervals at the 95% level were calculated using the following equation –

$$\text{Lower boundary of confidence interval} = \bar{X} - (1.96 \; X \; SE)$$

$$\text{Upper boundary of confidence interval} = \bar{X} + (1.96 \; X \; SE)$$

(Gardner and Altman, 1986, p. 748)

All statistical analysis was completed in SPSS (Version 19, IBM Corporation, New York, USA). The Shapiro-Wilk test was used to examine normality of data, which was confirmed. An independent t-tests were used to compare previously injured knees to matched controls absolute error scores with alpha levels set at $p<0.05$.

3.11 Peripheral / Muscular Fatigue and Knee Joint Position Sense

Participants

Twenty healthy participants (ten male, ten female, age 24.6±8.27 years, mass 72.1±11.65 kg, height 1.7±.0.10 m, BMI 23.9±3.15, GPPAQ range Inactive – Active, Tegner 5.5±1.19, KOOS 100±0, Lysholm 100±0) took part in the study and were recruited using convenience sampling techniques. All were free from lower extremity injury and neurological disease. Participants read an information sheet and provided written informed consent (see appendix five and six). This study was approved by the university ethics board (reference DC/SB/13/25).

Procedures

Participants wore shorts and removed the sock and shoe from their dominant leg. The participants were prepared for data collection by placing markers on the following anatomical points; a point on a line following the greater trochanter to the lateral epicondyle, close to the lateral epicondyle (placement of a marker directly on the greater trochanter is difficult due to clothing), the lateral epicondyle and the lateral malleolus of both legs (following Andersen *et al*., 1995).

Clinical Knee Joint Position Sense Measurement

Clinical knee JPS measurements were collected using the protocol determined as the most reliable by the previous study. The researcher gave a brief explanation of the JPS protocol before data collection to ensure the participant felt comfortable being blindfolded during the testing. The participant was then seated on the end of a physiotherapy plinth and blindfolded. The dominant leg was passively moved by the experimenter through 30°-60° of extension from a starting knee angle of 90° or through 60°-90° of flexion from a starting angle of 0° to a target angle at an angular velocity of 10°/s (Marks and Quinney, 1993). The order of the target angles was randomly allocated using randomly generated numbers. The participant then actively held the leg in this position for 5s. A photograph of the leg in the target position was taken using a standard camera (Casio Exilim, EX-FC100, Casio Electronics Co.,Ltd. London, UK) placed 3m from the sagittal plane of movement on a fixed level tripod (Camlink TP-2800,Camlink UK, Leicester, UK). The leg was then passively returned to the starting angle and the participant was instructed to actively move the same leg to the target angle and hold the leg in this position. Another photograph was taken and the participant instructed to move their leg

back to the starting position. The process was repeated five times for each target angle on the dominant leg pre and post fatigue exercise.

Peripheral or muscular fatigue protocol

A short warm-up involving five minutes self-paced cycling on a cycle ergometer (Wattbike, Wattbike Ltd, Nottingham, UK) and sub-maximal knee extension and flexion movements were conducted prior to data collection. Participants were given a familiarisation period prior to maximal testing (Dirnberger *et al*., 2012). In order to be certain participants reached a fatigued state maximum voluntary contraction of the included muscle groups was tested prior to the fatiguing exercises (Vollestad, 1997). Participants were seated on an adjustable chair and the trunk, hips and thigh were secured using the appropriate straps. The participant's lateral femoral epicondyle was aligned to the dynamometer rotational axis following the manufactures guidelines (Cybex NORM, Humac, CA, USA). Individual range of motion was set for each participant and a gravity compensation procedure was completed prior to testing. Maximal voluntary contractions of the knee flexor and knee extensor muscle groups were taken at 60°/s on the IKD (Cybex NORM, Humac, CA, USA). The best score (torque measure) and hence "optimal performance" was taken from five maximal trials (following Impellizzeri *et al*., 2008). The reliability of this maximal testing protocol has been previously reported by Impellizzeri *et al*. (2008); ICCs (2, 1) were 0.98 and 0.95 for extensor muscles and flexion muscles respectively. This provided a measure of "optimum performance" and the fatigued state was accepted at a percentage of this value. It has generally been accepted performance on three consecutive trials at 50% or below the maximum performance indicates the presence of muscular fatigue (Vollestad, 1997, Hiemstra *et al*., 2001). Participants were asked to continually concentrically extend and flex their knee joint maximally at 60°/s until they reached this threshold on three consecutive trials in both flexor and extensor muscle groups.

Data Reduction

Knee angles were measured using two-dimensional manual digitizing software (ImageJ, U. S. National Institutes of Health,, Maryland, USA, http://imagej.nih.gov/ij/, 1997-2012). Knee joint position sense was calculated from the average delta scores between target and reproduction angles across five flexion and five extension trials producing absolute error scores (AES) in which only magnitude was measured (Beynnon *et al*., 2000). Means, standard deviations and 95% confidence intervals were presented. All statistical analysis was completed in SPSS (Version 19, IBM Corporation, New York, USA). The Shapiro-Wilk test was used to

examine normality of data, which was confirmed. Paired sample t-tests were used to compare pre and post fatigue absolute error scores with alpha levels set at 0.05.

Chapter 4 Results

4.1 Normative Knee Joint Position Sense of an Adult UK Population

Results of the large scale normative JPS study are detailed in table 14. In total 116 participants were included in the study, 54 males and 62 females. There was a significant difference between JPS flexion (3.6±1.61°) and JPS extension (2.9±1.47°) absolute error scores (p=0.0001, r=0.10, figure eight). However, there were no significant effects of age group (p= 0.603 and p= 0.536) or gender (p=0.173 and p=0.948) on JPS flexion and extension absolute error scores respectively. There was also no significant effect of GPPAQ score on JPS flexion (p=0.691), however results indicated there was an effect of this exercise measure on JPS extension (p=0.04). Post-hoc analysis revealed a significantly greater absolute error score (p=0.017) for inactive participants compared to active participants (mean difference = 1.3°). There was a significant interaction between gender and GPPAQ score for JPS extension only (p=0.012) (see figure eight).

There were no significant correlations between JPS flexion absolute error scores and age (p=0.540), mass (p=0.687), height (p=0.977), BMI (p=0.598), Tegner (p=0.860), Lysholm (p=0.906) and KOOS (p=0.968). However, JPS extension absolute error score were significantly correlated to age (r= 0.277, p=0.003), height (r= -0.191, p=0.040), BMI (r=0.204, p=0.028), Tegner (r=-0.321, p=0.0001), Lysholm (r=-0.254, p=0.006) and KOOS (r=-0.247, p=0.008), but not mass (p=0.415). However, these correlations had a small to medium effect size (Cohen, 1992) at best.

Table 14. Normative knee joint position sense values of an adult UK population.

Age Group (years)	Gender Split	JPS Flexion (mean±SD°)	95% CIs		JPS Extension (mean±SD°)	95% CIs	
			lower	upper		lower	upper
15-29	Males (n=13)	3.6±1.65	2.7	4.5	2.6±1.32	1.9	3.3
	Females (n=16)	3.6±1.63	2.8	4.4	2.7±1.61	2.0	3.5
30-44	Males (n=13)	3.5±1.60	2.6	4.4	2.3±1.02	1.7	2.9
	Females (n=12)	4.3±1.90	3.2	5.4	2.7±0.82	2.2	3.2
45-59	Males (n=12)	3.5±1.19	2.8	4.2	2.7±1.31	2.0	3.4
	Females (n=13)	3.4±1.61	2.5	4.3	3.0±1.31	2.3	3.7
60-74	Males (n=11)	3.3±1.10	2.6	4.0	3.3±1.91	2.2	4.4
	Females (n=15)	4.1±2.15	3.0	5.2	3.4±1.35	2.7	4.1
75+	Males (n=5)	3.0±1.27	1.9	4.1	3.4±2.41	1.3	5.5
	Females (n=6)	3.1±1.30	2.1	4.1	4.3±1.62	3.0	5.6
Mean		**3.6±1.61**	**3.3**	**3.9**	**2.9±1.47**	**2.6**	**3.2**
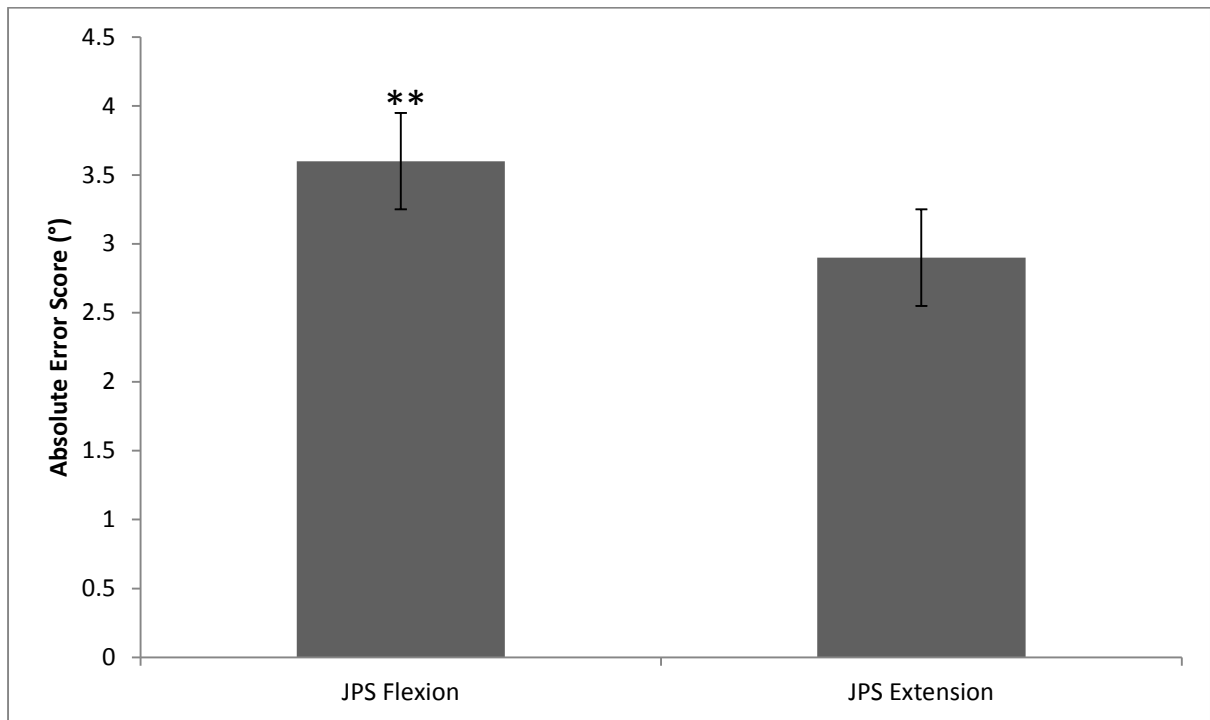
Figure 8. Mean and Standard Error JPS Flexion and Extension Scores for a normative population. **Flexion scores were significantly higher (p=0.0001) than extension scores.
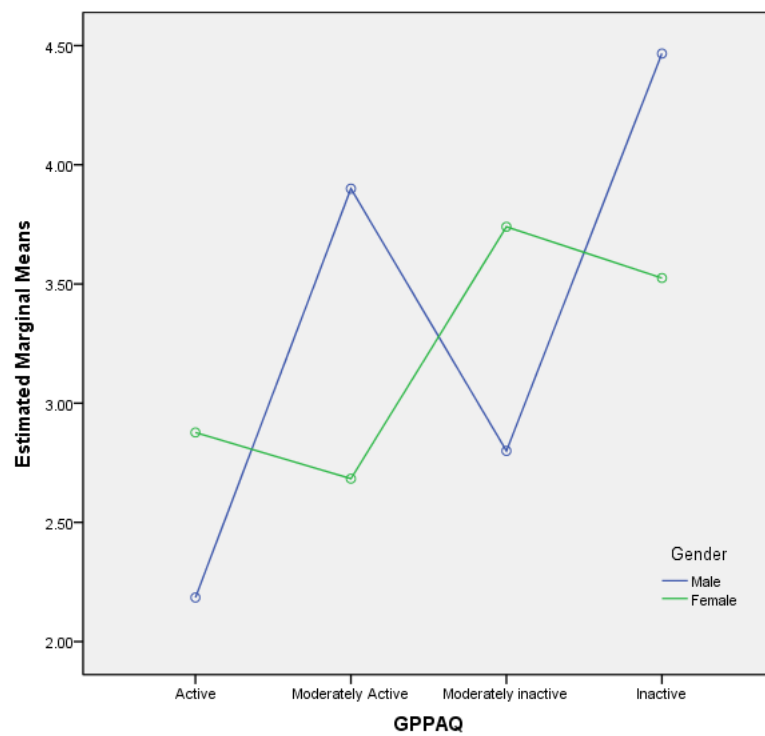
Figure 9. A significant interaction (p=0.012) between Gender and GPPAQ scores from JPS extension data.
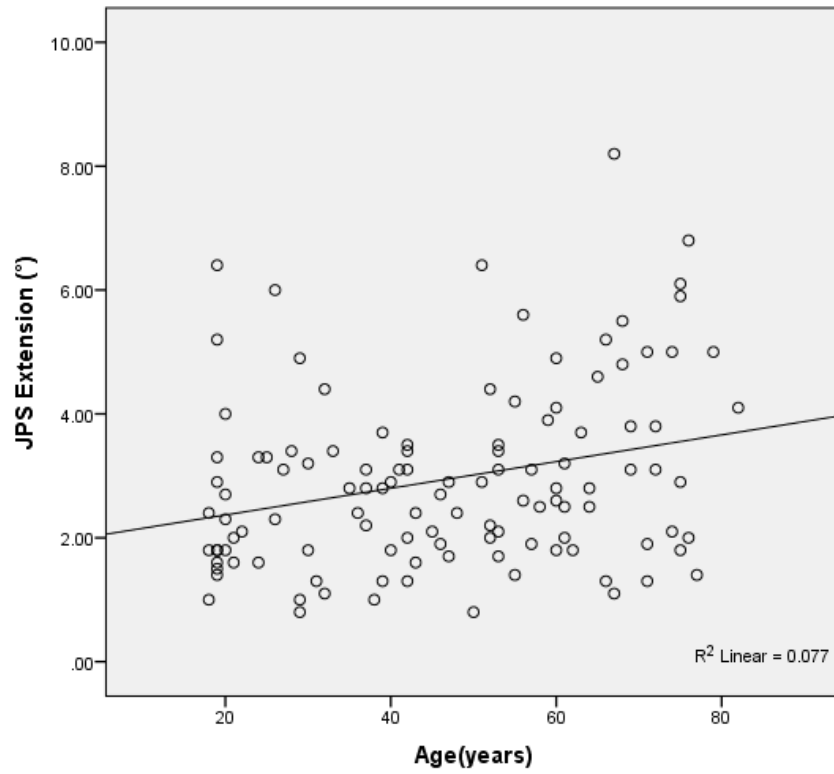
. **Figure 10.** Correlation (r = 0.271) between JPS extension absolute error scores and age.
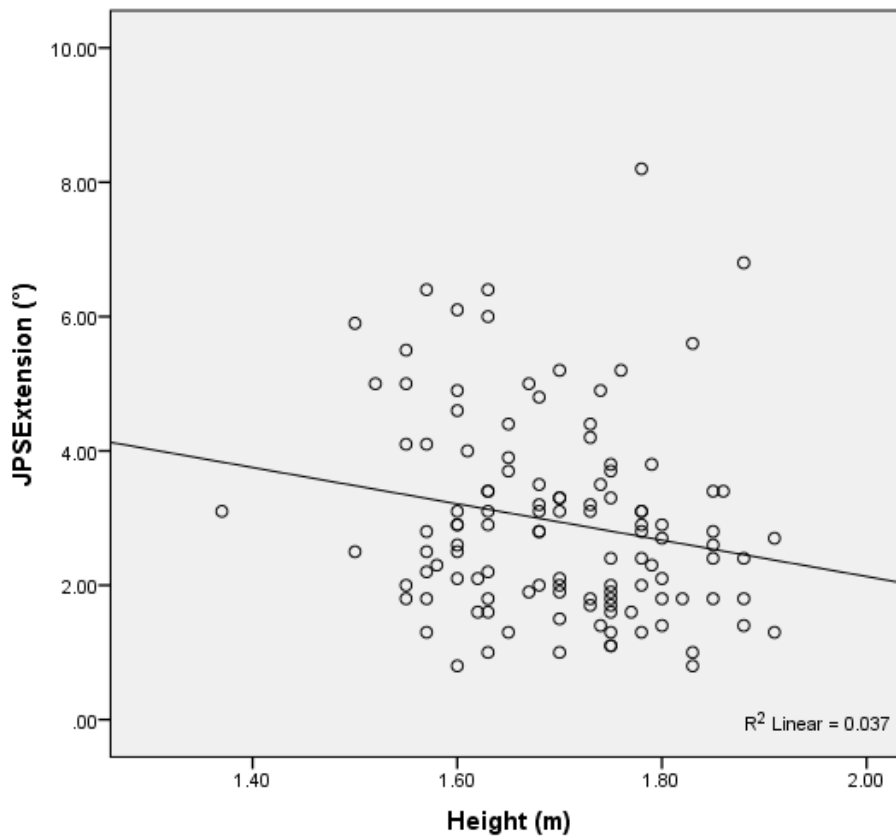
Figure 11. Correlation (r = -0.191) between JPS extension absolute error scores and height.
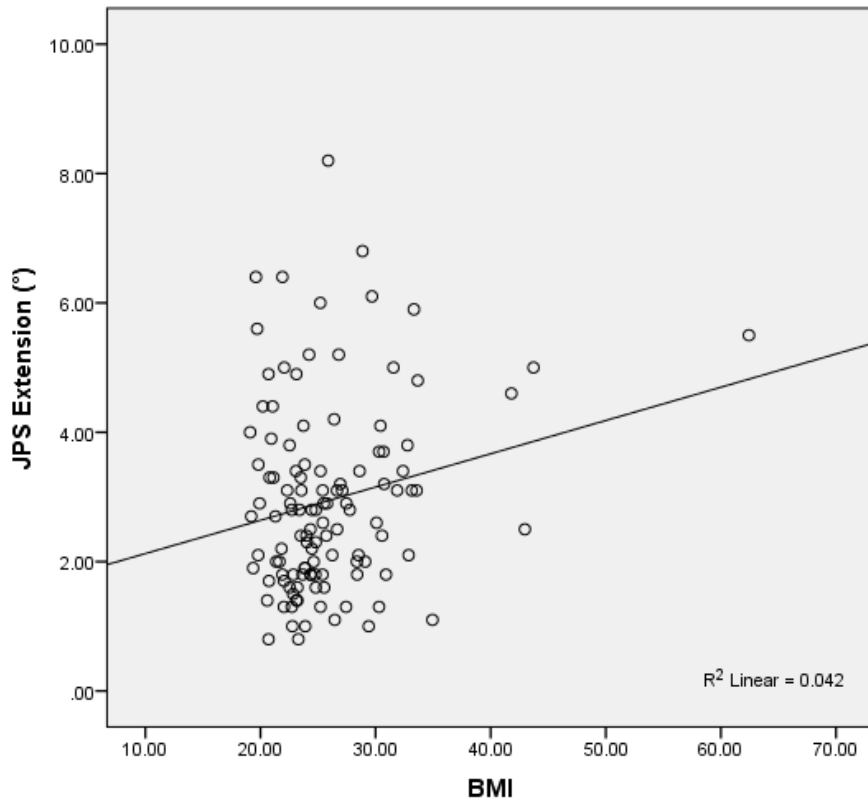
Figure 12. Correlation (r = 0.204) between JPS extension absolute error scores and BMI.
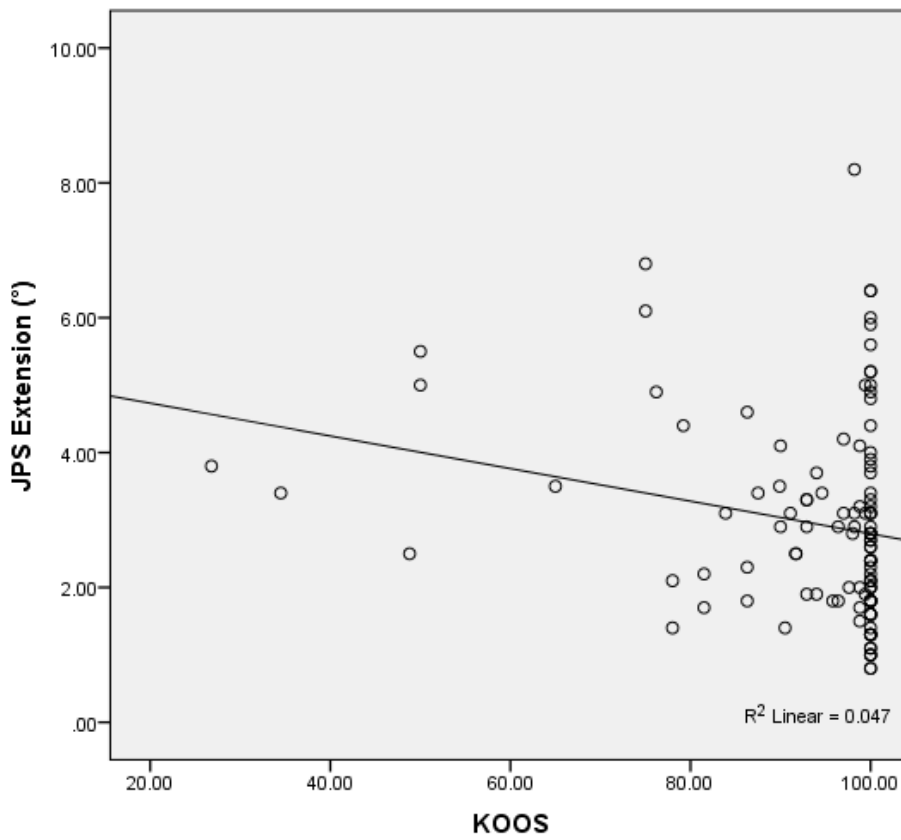
Figure 13. Correlation (r = -0.247) between JPS extension absolute error scores and KOOS.
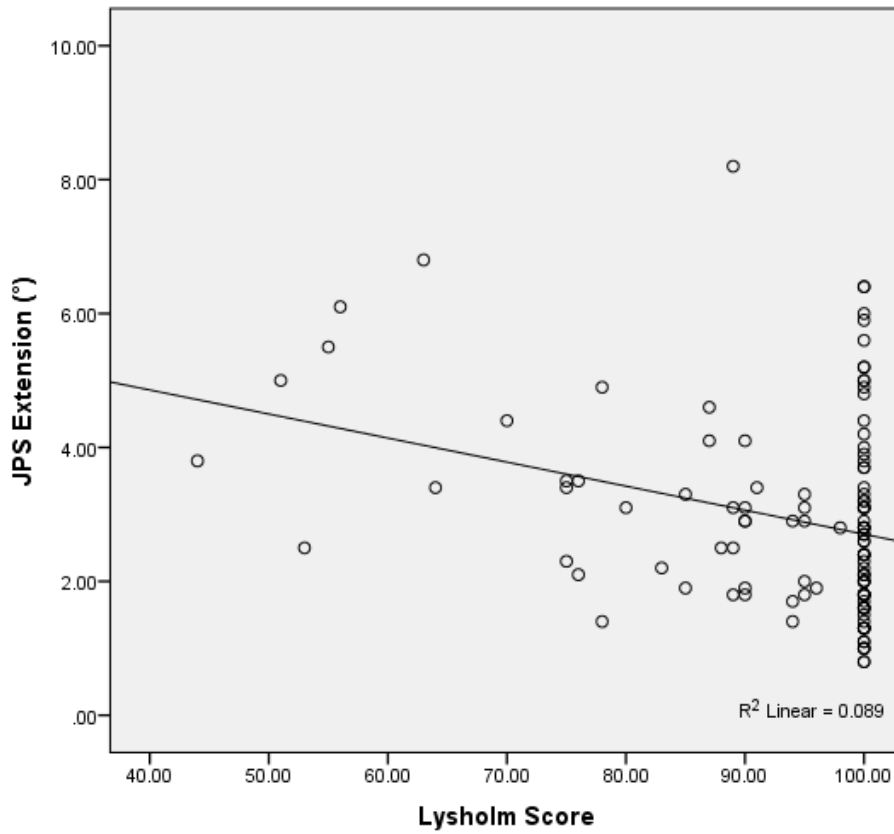
Figure 14. Correlation (r = -0.254) between JPS extension absolute error scores and Lysholm Score.
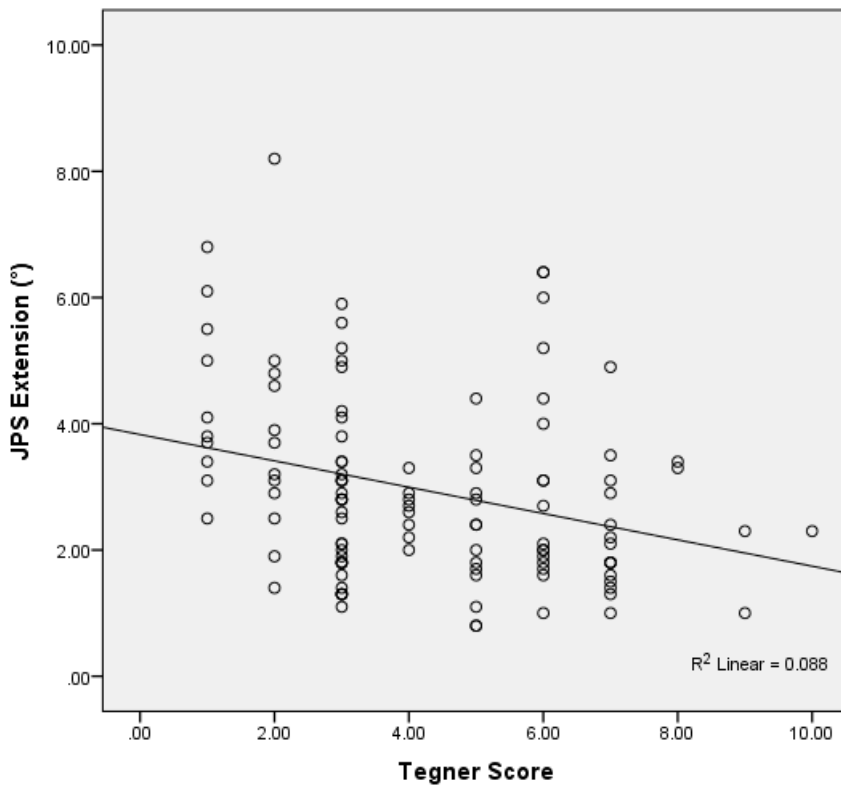
Figure 15. Correlation (r = -0.231) between JPS extension absolute error scores and Tegner Score.

4.2 ACL injured Knee Joint Position Sense

4.2.1 Non-athletic Population with ACL Deficiency

Figure 16 illustrates JPS differences between non-athletic ACL deficient patients, their contralateral leg and an external control group. The average JPS error score in the ACL deficient group was 7.9°±3.6 (95% CI [6.3, 9.5]). In comparison, the contralateral leg and control group error scores were 2°±1.6 (95% CI [1.3, 2.7]) and 2.6°±0.9 (95% CI [2.2, 3.0]) respectively. Statistical analysis revealed significantly greater JPS ability in the control group (p=0.0001) and contralateral leg (p=0.0001) when compared to the ACL deficient leg. However, the external control group also had a significantly lower JPS ability than the ACL patient's contralateral knee (p=0.02).
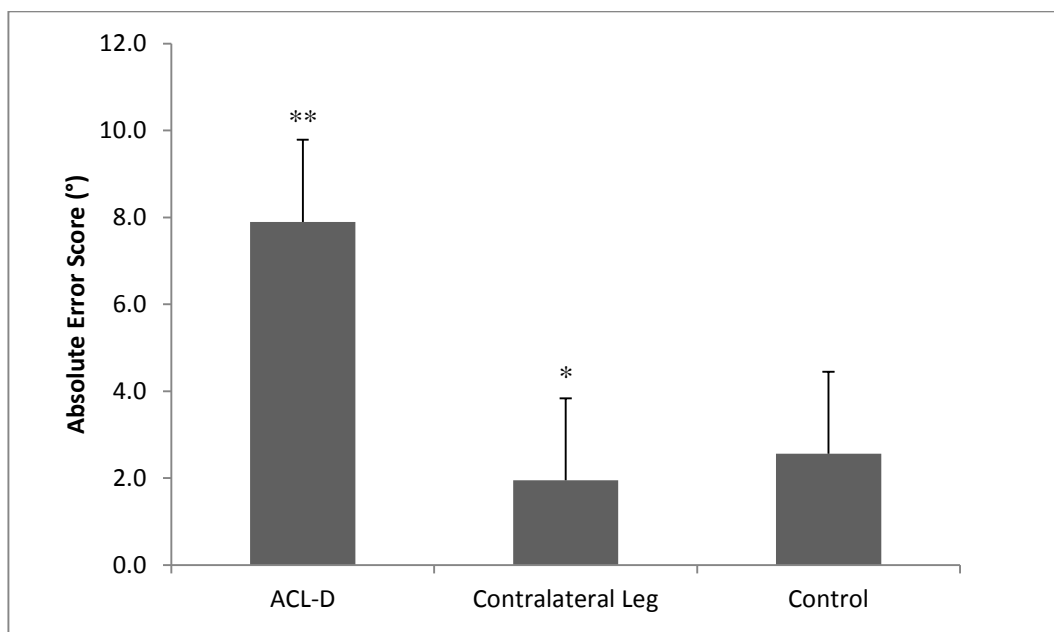
Figure 16. Mean and Standard Error JPS Absolute Error Scores for a non-athletic ACL deficient and normative population. **Significantly different to contralateral leg and control group. *Significantly different to control group.

4.2.2 Elite-athletic Population with ACL reconstructions

Figures 17 and 18 display the JPS differences between elite-athletic ACL reconstructed patients, their contralateral leg and a matched external control group. The elite athletes demonstrated a greater mean error score of 8.1°±1.24 (95% CI [7.3, 8.9]) and hence lower joint position sense ability in knee flexion when compared to their contralateral leg mean score of 3.5°±0.72 (95% CI [3.1, 4.0]) (p=0.0001, r=0.98) and an external control group mean score of 3.1°±1.84 (95% CI [2.0, 4.2]) (p=0.0001, r=0.92). This finding was repeated in

knee extension JPS; athletes had poorer JPS compared to contralateral side (p=0.0001. r=0.98) and external controls (p=0.0001, r=0.91). The average error score on the reconstructed side was 7.2°±0.97 (95% CI [6.6, 7.8]) compared to the contralateral side mean error score of 1.9°±0.47 (95% CI [1.6, 2.2]) and the external control mean error score of 2.8°±1.94 (95% CI [1.6, 4.0]). The contralateral leg of the injured athletes displayed similar JPS ability to external controls for both knee flexion and knee extension respectively (p=0.555, r=0.187).
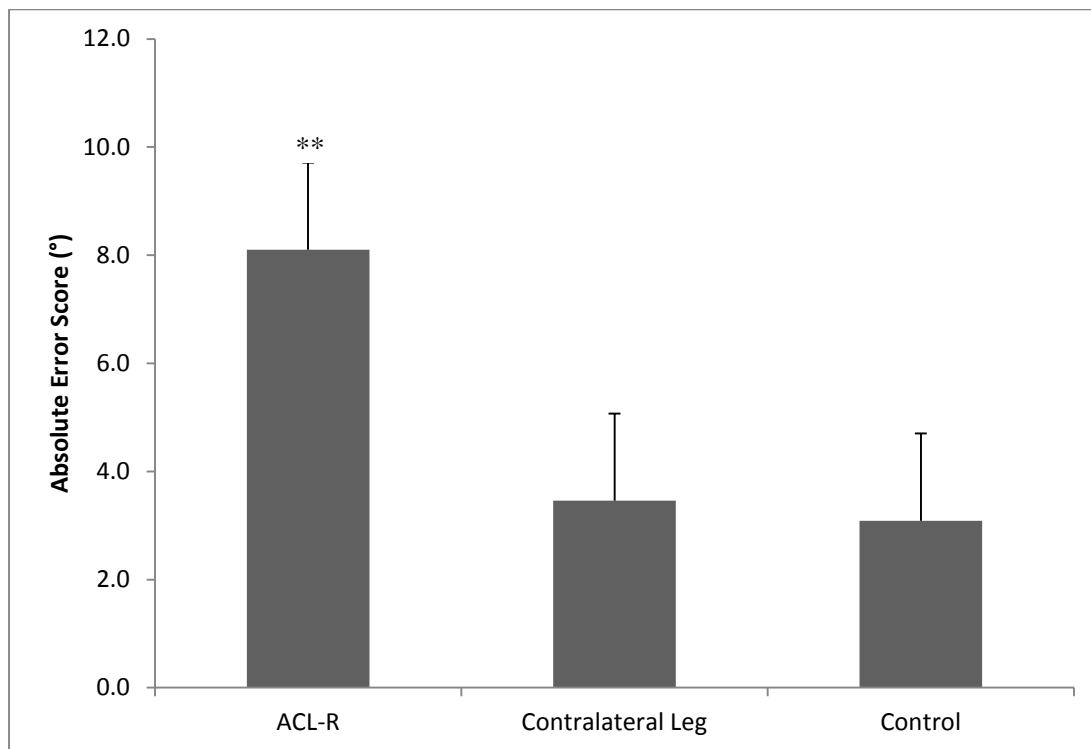
Figure 17. Mean and Standard Error JPS into flexion Absolute Error Scores for an elite-athletic ACL reconstructed and normative population. **Significantly different to contralateral leg and control group.
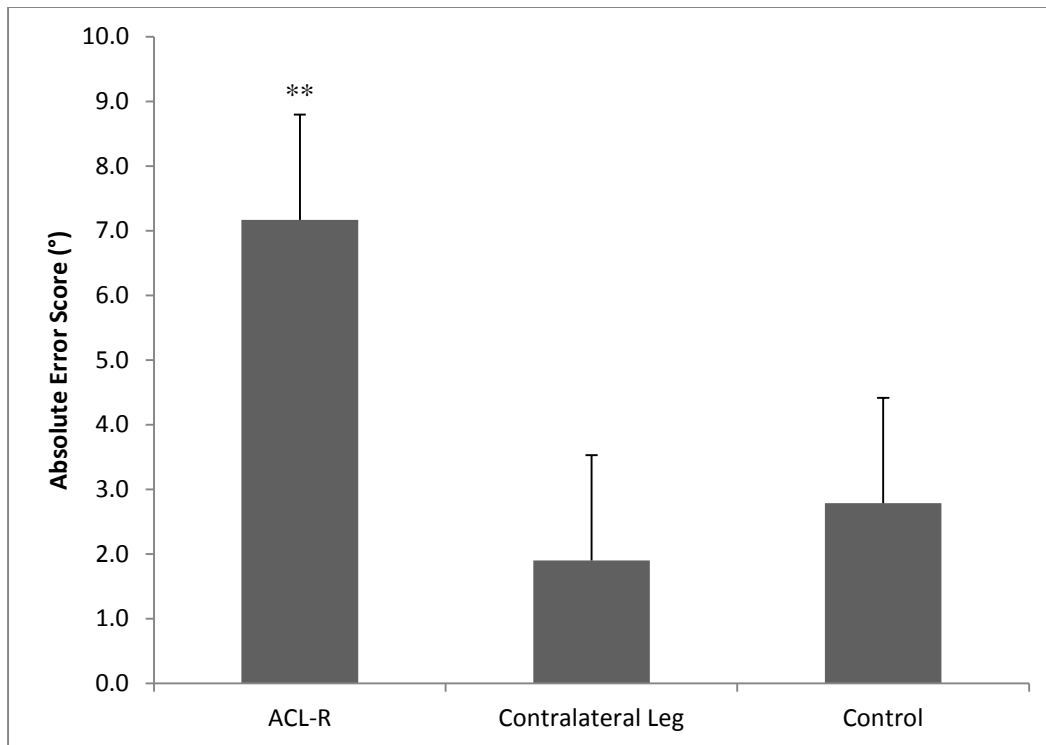
Figure 18. Mean and Standard Error JPS into extension Absolute Error Scores for an elite-athletic ACL reconstructed and normative population. **Significantly different to contralateral leg and control group.

4.3 Other Knee Injuries and Knee Joint Position Sense

Data from patients with other knee injuries excluding ligament damage did not demonstrate a reduced joint position sense ability for either knee flexion (p=0.638) or knee extension (p=0.861) compared to age and activity matched controls. The injuries included in this sample were early stage OA (Grade 1), patellofemoral pain syndrome, patella re-alignment, cartilage and/or menisci damage, knee laxity and tibial surgery. Results are included in table 15.

Table 15. Mean and standard error JPS absolute error scores for knee injured patients and external matched controls.

Direction	Group	Mean±SD (°)	95% Cis	
			Lower	Upper
JPS Flexion	Injured (n=15)	3.7±1.75	2.8	4.6
	External Control (n=15)	3.4±1.46	2.7	4.1
JPS Extension	Injured (n=15)	2.8±0.91	2.3	3.3
	External Control (n=15)	2.9±1.14	2.3	3.5

4.4 The Effect of Peripheral/ Muscular Fatigue on Knee Joint Position Sense.

The mean (±SD) maximum voluntary contraction into knee flexion and extension was 78.7 N.m (±22.8) and 177.1 N.m (±39.0) respectively. Results of the analysis revealed no effect of the fatiguing protocol on either JPS flexion (p=0.729) or JPS extension (p=0.492). In fact, the data suggested some participants' JPS score actually improved following fatiguing; However on average JPS flexion error scores reduced by 0.17° and JPS extension error scores reduced by 0.14°. However, these decreases were not statistically significant (figure 19).
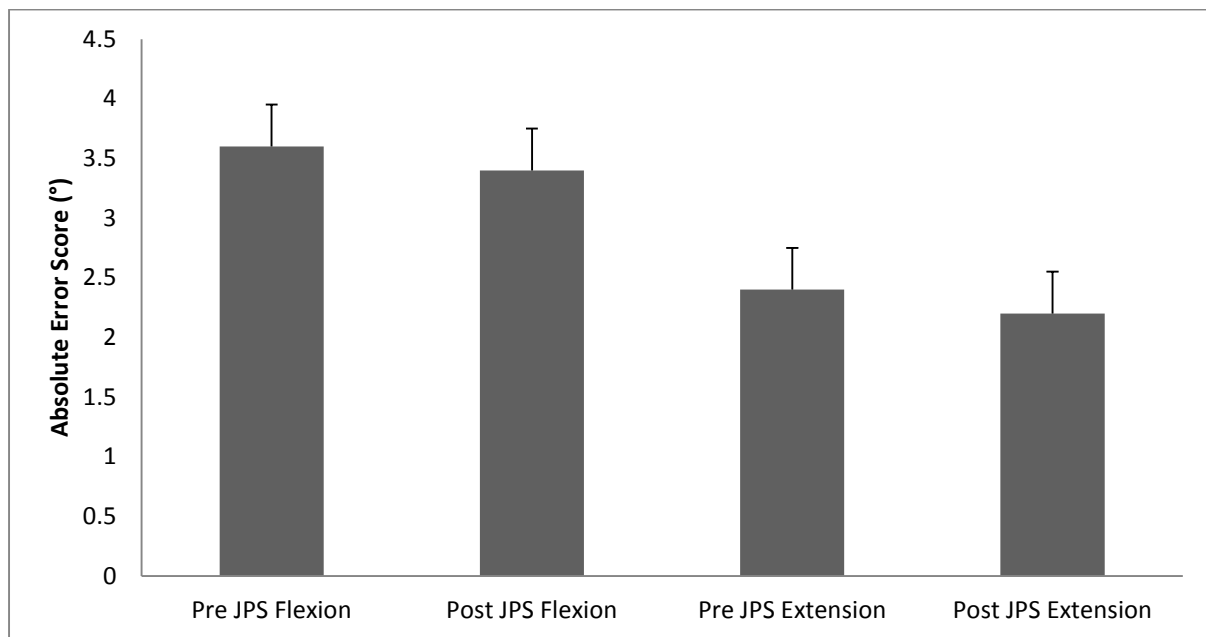
Figure 19. Mean and Standard Error JPS Absolute Error Scores pre and post fatiguing protocol.

Chapter 5 Discussion

5.0 Introduction

The global aim of this thesis was divided into two sub-sections. The first aim involved measurement; to find the optimal condition to record knee joint position sense ability. This included the reliability, validity and learning effect of existing knee JPS methods. The second aim involved implementation of this tool to report the effects of various independent variables on knee joint position sense ability. These variables included age, gender, BMI, physical activity, self-reported knee condition, ACL injury and muscular fatigue. The results of each of these studies are discussed below.

5.1 Optimum Environment for Knee Joint Position Sense Measurement

Recently Suetterlin and Sayer (2014) stated that there has been little progress in the clinical assessment of proprioception. Specifically, there has been a lack of reliability and validity analysis of the current knee joint position sense measures. Therefore, the reliability and validity of knee joint position measurement was tested using appropriate statistical analysis. It was concluded five trials of knee joint position sense in the sitting position, with either leg (the dominant leg was used in this thesis), into flexion through 60°-90° of motion and into extension through 30°-60° of motion then calculating absolute error score is the most reliable method of establishing knee joint position sense. Validity of this method using an IKD was confirmed for knee joint position sense into flexion but not knee joint position sense into extension. These findings are discussed in the following two sections.

5.1.1 Test-Retest Reliability of Knee Joint Position Sense Measurement

General reliability can be defined as the reproducibility or consistency of a measure (Atkinson and Nevill, 1998). Hopkins (2000) states test-retest reliability is one of the most important aspects of research, critical to the understanding of measurement error. The definition of test-retest reliability is concerned with the reproducibility of an individual's values across repeat data collection sessions (Hopkins, 2000). Clinical practitioners may use measures of JPS to monitor progress in a rehabilitation programme, or with athletes across a season. Therefore, the reliability of knee JPS is critical to representative results. The test-retest reliability of knee joint position sense was considered using ICC scores across two separate testing days a week apart. In addition, the effect of six independent variables, which represents the JPS methodological choices clinical practitioners must make when measuring knee JPS, were analysed. These included number of trials, type of error score (relative or absolute), leg

(dominant or non-dominant), range of motion (low, medium, high), direction (flexion or extension) and condition (sitting, prone or active).

To the author's knowledge there is only one previous paper that considered the learning effect and hence the number of trials necessary for consistent knee JPS scores. Selfe *et al*., (2006) investigated the effect of the number of JPS trials in patients with patellofemoral pain syndrome (PFPS). They concluded five trials are necessary for consistent absolute error score results. This is supported by the results of the current reliability study; there were no significant differences between five, 10 or 15 trials. This is important information for clinicians and researchers, five trials is sufficient for representative knee joint position scores. Selfe *et al*., (2006) also considered relative and absolute error scores, indicating the type of error score used produces significantly different knee JPS results in PFPS patients. Olsson *et al*., (2004) also states relative and absolute error scores are significantly different in healthy patients. This is again supported in the current reliability analysis; relative error scores were significantly different to absolute error scores in uninjured populations. Relative error scores (RES) indicate magnitude and direction of error; either an over-estimation or under-estimation of the target angle. Whereas, absolute error scores only consider the magnitude of error. It should, therefore, be expected these calculations will elicit different results and clinicians should keep their choice of score consistent throughout assessments.

Further analysis revealed relative error scores were affected by leg and range of motion, whereas absolute error scores were not. This may be because the direction of error aspect of the error score is more sensitive to differences in leg and range of motion. However, if clinicians wanted to make an assessment of knee joint position using RES they would have to measure both legs through three range of motions which would be significantly time consuming. It has also been suggested average relative error scores mask joint position sense ability, as the average of repeated trials can incorrectly reduce the error score (Olsson *et al*., 2004). Furthermore, no literature to date has correlated direction of error (RES) and increased risk of a particular knee injury (Sterner *et al*., 1998), only that poor JPS may lead to increased risk of injury. Therefore it may not be necessary to measure the direction of error, just the magnitude of the error. Other limitations of relative error scores include poor reliability (Clark *et al*., 1995), occurrence of drift in scores over time (Wann and Ibrahim, 1992) and significant learning effects (Redding and Wallace, 1995). Therefore, it may be concluded that AES should be used for clinical measures of knee joint position sense.

Absolute error scores were not affected by choice of leg (dominant or non-dominant), clinicians can use either leg to test knee JPS in uninjured populations. This has been supported in studies by Stillman (2000), Kiefer *et al* (1998), Beard *et al*., (1993), Ageberg *et al*., (2007), Boerboom *et al*., (2008) Euzet and Gahery (1995) and Herrington (2005). It is perhaps intuitive that the number of proprioceptors located in the muscle, joint and skin in the lower limbs may be comparable bilaterally and hence knee joint position sense may also be significantly similar between legs. Although, Han *et al*., (2013c) did report bilateral position sense of both upper and lower limbs and indicated non-dominant sides may have an increased ability when compared to the corresponding dominant joint. Non-dominant sides tend to have a stabilising role in most motor activities and hence have more experiences of position sense; this may explain the increased non-dominant side ability in the Han *et al*., (2013c) paper. As is the theme throughout this thesis, position sense ability was measured differently in all studies considering bilateral proprioceptive ability and may explain the discrepancies. However the current thesis was the first study to use a reliable and valid clinical method to compare side to side knee position sense and found no significant differences ($p > 0.05$). Future work should use the validated and reliable method reported in this thesis to confirm bi-lateral symmetry of knee position sense.

The range of motion did not significantly affect absolute error scores however there was a significant difference between flexion and extension directions. The most reliable (highest ICC) was attributed to a high-range of motion in to flexion and a mid-range of motion in to extension, this procedure should be used in knee joint position measurements. Range of motion may not affect JPS scores as it has been suggested receptors from joint, skin and muscle work together throughout the range of motion to produce one "final common output" (Johansson *et al*., 1991b). Therefore, although different receptors may dominate across the range of motion, for example muscles during mid-range and joint and skin during high-range, the output across the range of motion produces effective and comparable joint position sense. However, direction did affect joint position sense; specifically knee extension trials produced significantly higher joint position error scores than knee flexion trials and the effect size was large (0.74). The most reliable target angle into flexion was around the vertical position (i.e. between 60-90° of flexion). Rodier *et al*., (1991) also found this target position to produce maximal performance of knee joint position sense. They explain that the direction of gravitational forces orientates the coordinate system used to position joints in space, and further, this knee vertical joint position may be used as a basic reference value in human positioning (Reider *et al*., 1991).

Indeed this position allows balanced afferent input from both agonist and antagonist muscles and such may require less complex neural processing. This may allow for smaller reproduction errors than when compared to the most reliable extension position (between 30-60° from 90°).

Three conditions were considered, sitting, prone and active (using a "Total Trainer, see figure 6). The prone condition produced the highest error score, hence worst JPS. The most reliable JPS scores (highest ICC scores) were produced in the sitting condition, 12 out of 12 sitting variables were classed as having "excellent" reliability (Shrout and Fleiss, 1979). This is in comparison to the active, "Total Trainer" condition in which only one out of 12 variables was of "excellent" reliability (Shrout and Fleiss, 1979). Absolute error scores were significantly different between conditions; as such a sitting condition should be used when measuring knee joint position sense. Previous research has suggested closed chain trials and active – active JPS tests (such as the "Total Trainer" protocol) reveal superior JPS measures as they replicate the body's natural movement and planes and stimulates all involved mechanoreceptors (Andersen *et al*., 1995). It is also suggested this type of protocol can allow proprioceptive feedback from the surrounding joints (Ghaisi and Akabari, 2007) and hence provide a more "global" measure of JPS. It follows the active condition may have been thought would produce the best JPS score; however in this thesis this was not the case. The protocol design attempted to create a "semi-loaded" or "semi-active" environment as previous research suggests older participants can not complete fully weight-bearing JPS measurement protocols (Petrella *et al*., 1997). However, the protocol in this thesis involved participants pushing off a wall; this required appropriate muscle strength to control knee flexion and extension and may have affected results. The movement may be more "unnatural" than the standing protocols used in other closed chain active-active studies and therefore participants may not have been in an environment to produce their best joint position sense ability.

Furthermore, it may be the sitting condition, stated as a passive – active protocol, may in fact be a semi-active – active protocol. Stillman's (2000) experiment using EMG of the quadriceps and hamstring muscle groups demonstrated how difficult it is for participants to be totally passive in the passive positioning of a target angle. Stillman's (2000) results illustrated both agonist and antagonist muscle groups were activated throughout all "passive" movements and clinicians were unable to identify this activation. Grigg (1994) states muscle tension increases proprioception ability. As such, the sitting protocol utilised in this thesis may afford participants the opportunity to activate receptors to a degree in a supported range of motion to the target angle then fully activate receptors in the matching movement. This should not be

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seen as a limitation. Firstly, as Stillman (2000) demonstrates, it may be near impossible to ask participants to be truly passive in the positioning phase; therefore we should perhaps not aim for or claim this in JPS protocols. The supported active condition (called passive) may also provide greater ecological validity, participants would be using active receptors during normal movement, and thus it is valid for practitioners to encompass active receptors activity in the testing of JPS. This may explain why the sitting condition produced better JPS scores than the active condition; the protocol was in fact a semi-active – active protocol in a more natural position (sitting) than on the "Total Trainer".

An important observation from the reliability analysis is the smallest detectable differences were comparable to the mean error scores. For example, the protocol highlighted as best practice in this thesis had an absolute error scores of 3.3° during knee flexion and an accompanying smallest detectable difference score of 1.1° and absolute error scores of 2.5° during extension and an accompanying smallest detectable difference score 1.7°. This suggests 33% and 67% of flexion and extension error scores respectively may in fact be measurement error. This is an important finding for clinicians as knee joint position sense ability during rehabilitation or pre-habilitation programmes may be masked by measurement error.

The reliability of other joint position sense measures has been reported. Deshpande *et al*., (2003) reported excellent reliability of ankle position sense measurements. However Strimpakos *et al*., (2006) found poor to moderate at best for standing and sitting cervical joint position sense. This suggests each joint may require individual protocols and measurements to ensure results are reliable.

5.1.2 Construct validity of knee joint position sense measurement

Construct validity was confirmed for knee flexion joint position sense but not knee extension joint position sense. The IKD data provided significantly greater error scores than the clinical data when considering knee extension. It is possible in the IKD setting participants had to adapt to the addition of the lever arm increasing the mass of the leg and the torque required to extend the knee, thus, effort was not as natural when compared to the clinical setting. This may not have the same effect on knee flexion as the torque required in this direction would be assisted by gravity. Another feasible explanation was the seating in both tests. In the clinical test condition participants were seated on the edge of a plinth and hence were not conscious of a back rest and could use the pelvis to assist knee extension and the associated hamstring

lengthening. In the IKD setting participants were seated on the edge of the seat and although not supported by the back rest, may have been less likely to use the pelvis to assist knee extension and hence perhaps a less natural knee extension movement. Results of the validity study have important implications for clinicians. The clinical measurement of knee joint position sense produced similar (knee flexion) and improved (knee extension) absolute error scores compared to the IKD setting. Therefore knee joint position sense can be measured in a clinical setting, expensive IKD equipment or self-built pulley systems are not necessary.

5.2 Normative Levels of Knee Joint Position Sense Measurement

Normative data of knee joint position sense was collected across an age and gender representative sample of a large scale population. There is a shortage of normative knee joint position sense values; in fact no study to date has reported normative values using a reliable and valid measurement technique. Stillman (2000) has presented knee joint position sense values from 82 young healthy adults (53 females, 29 males, 20.2±1.6 years). Stillman used an ipsilateral knee flexion matching technique to a range of target angles from both dominant and non-dominant legs. Absolute errors ranged from 2.1° at 20° of knee flexion to 3.4° at 50° of knee flexion. The results of the current thesis are comparable to these values; in the groups aged between 15 and 29 years JPS flexion errors were 3.6° and JPS extension errors were 2.65°. Stillman (2000) also reported knee joint position sense absolute errors for a healthy older aged group (14 females, 11 males, 57.6±10.3 years). Four test positions were considered; 20°, 30°, 40° and 50° of knee flexion, absolute error values were 2.5°, 2.6°, 3.3° and 4° respectively. These results are again consistent with findings in this thesis; the group aged 45-59 years had an average knee flexion absolute error score of 3.45° and knee extension score of 2.85° and the group aged 60-74 years had an average knee flexion absolute error score of 3.7° and knee extension score of 3.35°. Burgess *et al*., (1982) and Callaghan also suggested a more general value for "normal" joint position errors of error of less than 5°. It appears in this thesis that knee joint position sense absolute error scores normally range from 2.3° to 4.3° in uninjured populations. Practitioners may use this range when pre-screening athletes when identifying those more at risk due to abnormal knee position sense ability. Practitioners may also use this range during rehabilitation, if they would like to rehabilitate their patient back to a "normal" level. Although, this must be done with caution as large scale normative data on specific knee pathologies such as ACL injured patients has not been completed therefore, it is still unknown if this is possible.

Goble *et al*., (2010) provided pilot data for arm joint position sense values across the age groups (see figure 20). This data comes from the elbow joint using ipsilateral matching techniques to 30 degrees in the preferred arm. Although exact data values are not provided, elbow position sense absolute error values range from approximately 3.6° in the young adult (20-30 years) to approximately 5.8° in the child group (8-10 years). As children were not considered in the current thesis, the next highest absolute error score will be considered; this was produced by the older people group (70 years and over) and was approximately 4.6°.
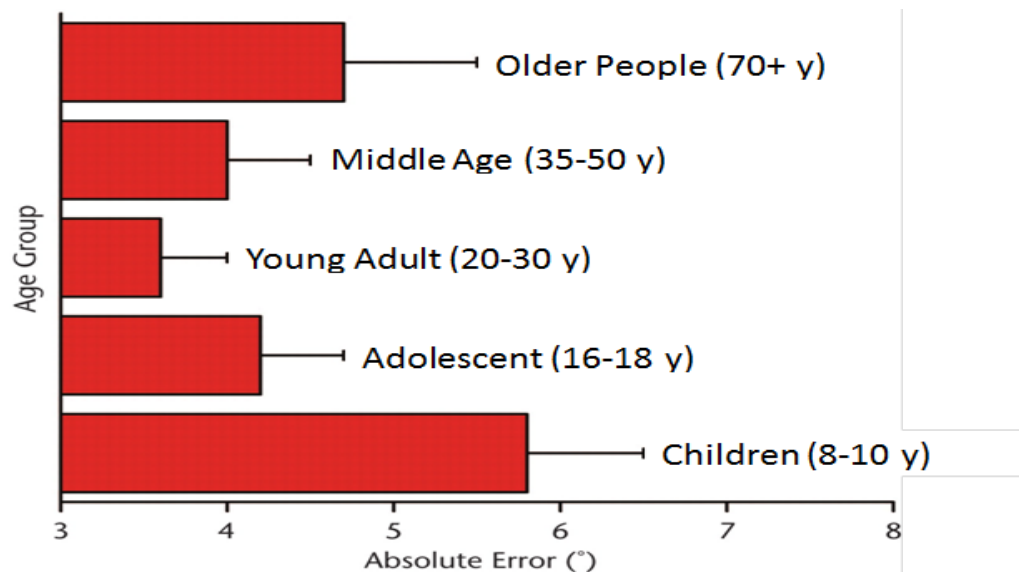
Figure 20. Average absolute errors in the elbow ipsilateral matching of 30° targets for different cross sections of the human life span (taken from Goble *et al*., 2010).

Again, these values are similar to the knee position sense measures reported in this thesis. It therefore might be suggested joint position sense is similar in the knee and elbow joint. However, alternative research (Li and Wu, 2014) presented a higher value for elbow flexion absolute error score for elderly groups (6.7°±5.71). Further, Li and Wu (2014) reported shoulder flexion (8.1°±5.70), shoulder adduction (10.7°±6.63) and wrist extension (12.6°±7.7) absolute error scores. These are also higher than the reported knee absolute error scores in this thesis. The greatest difference in position sense reported between joints was over 10° when comparing knee extension and wrist extension of participants aged 30-44 years (Li and Wu, 2014). Han *et al*., (2013b, 2013c) compared joint positon sense differences between joints in the body to explore the presence of a general proprioceptive ability or site-specific proprioceptive ability. Results provided evidence for a site-specific proprioceptive ability; Pearson's correlation coefficients were not significant for any relationships between ankle, knee, shoulder, spine and finger joint position sense. This is supported by Paschalis *et al*.,

(2009) who demonstrated significant differences between proprioceptive ability (both position and movement sense) of the arms and legs; the arms had better proprioceptive ability than the legs. Burgess *et al*., (1982) also reported differences in joint proprioception between the elbow, knee and hip. It is, therefore, apparent joints have different position sense ability; in fact evidence suggests position sense tends to be better for the more proximal joints compared to distal ones (Herter *et al*., 2014, Semmler and Miles, 2006), this may be due to the distribution of muscle spindles spanning each joint.

These results are important to the clinical practitioner. It is thought there is a greater risk of joint injury when there is a pre-existing and potentially genetic global proprioceptive deficit (Han *et al*., 2013b). However, the existence of a global genetic proprioceptive ability is rejected in favour of a site-specific ability (Han *et al*., 2013b, 2013c). Therefore, practitioners should not assume if patients do not have comparative knee absolute errors scores to the data provided in this thesis, then global "proprioceptive training" (e.g. Swanik *et al*., 1997) will improve this deficit. Future studies should aim to provide more normative proprioceptive data on all joints using a reliable and valid method. Furthermore, more specific "site-training" of proprioception could be developed.

In addition to knee joint position measures, this thesis also provide the normative data of knee injury and osteoarthritis outcome scores (KOOS) for an injured UK population. Qualitatively, it is apparent none of the five age groups considered scored the predicted 100 defined as "no knee problems" (Paradowski *et al*., 2006). This will be discussed in section 5.2.5. The effects of movement direction (knee flexion and extension), age (15-19 years, 30-44 years, 45-59 years, 60-74 years and 75+ years), activity level (GPPAQ and Tegner), BMI (mass and height) and knee condition (KOOS and Lysholm) were also considered in the thesis. The following sections discuss each variable individually.

5.2.1 The Effect of Knee Flexion and Extension on Knee Joint Position Sense Measurement

The normative population data revealed greater knee joint position error scores into flexion than extension. The improved knee position sense into extension may be attributed to the type of agonist muscle group involved in the movements. Knee extension may provide greater levels of afferent feedback due to greater muscle spindle and Golgi tendon organ activation in the larger quadriceps muscle group compared to the smaller hamstring muscle group contraction

during knee flexion. Hip extensor muscle groups are more dominant in knee extension and contribute to knee extension movements, potentially providing additional joint afferent information and hence a heightened joint position sense in this movement direction. Participants are also working against gravity in knee extension trials, which require greater torque than knee flexion and hence greater muscle contraction and muscle spindle activation which may result in greater proprioception feedback.

The knee flexion protocol was also more dependent on muscular strength as the testing began at 0° and the participant had to move from a high torque position to a low torque target angle. This may have provided a more challenging test than the knee extension task; the participants may have become more concerned with maintaining 0° than the target angle.

Previous research has considered direction of movement and proprioception. Proske *et al.*, (2000) investigated the effects of joint direction and movement sense. Their results specified TTDPM tended to increase towards flexion, they suggested this is because afferent information is reduced when muscle spindles are shortened compared to lengthen. However their work did not consider joint position sense. Friden *et al.*, (1996) also reported differences in TTDPM tests between flexion and extension but did also investigate knee joint position sense using an active reproduction protocol. Friden *et al.*, (1996) reported lower error scores for knee flexion movements compared to knee extension, attributing this difference to superior hamstring afferent feedback. However different starting positions, target positions and angular velocities were used in comparison to the current study and therefore comparisons should be completed with caution. Drouin *et al.*, (2003) also considered direction and joint position sense and found no significant differences between flexion and extension again using a different joint position sense protocol. Previous studies do not support data in this thesis where previous studies show knee extension trials produced significantly higher joint position error scores than knee flexion trials. However, the normative data set in this thesis came from a power calculation to provide an appropriate sample size producing 90% power and alpha set at 0.05 this result may be more representative than previous studies.

There is a limited amount of research considering the effects of knee direction on joint position sense and hence it is difficult to practically apply the findings of the current study to practitioners. There may be a difference between knee flexion and extension joint position sense and hence both directions should be used in clinical joint position sense testing. However it is also important to consider the magnitude of this difference, the current study revealed an

average difference of just 0.7° difference between knee flexion and extension absolute error scores. It can be questioned as to how clinically significant less than one degree is to a patient. Therefore future research should consider the correlation between knee JPS ability and functional performance.

5.2.2 The Effect of Age on Knee Joint Position Sense Measurement

Results of this thesis reveal no significant differences between the five age groups in either knee flexion or extension absolute error scores (p= 0.603 and p= 0.536 respectively). This is in agreement with Pickard *et al*., (2003) who also did not find significant differences between young and old populations in joint proprioception. However, Pickard *et al*., (2003) did not state there was therefore not an effect of age on proprioception; rather the older group participated in regular physical activity which may have negated a proprioceptive decline. Indeed, evidence has indicated regular exercise attenuates the decline of proprioception with age (see section 2.5.3). The majority of participants in the elderly groups in the current study took part in some form of exercise; 45-59, 60-74 and 75+ years of age reported average Tegner scores of 4.1, 2.5 and 2.2 respectively and some participants in each age group reported a GPPAQ score of Active. This may have improved JPS ability. However, there was a significant positive, although weak, correlation between joint position sense into extension and age (r= 0.277, p=0.003), specifically as age increased, joint position sense absolute error scores also increase showing as age increases knee JPS ability may indeed decrease.

The effect of age on lower limb proprioception has been considered in previous research (Ribeiro and Oliveira, 2010, Hurley *et al*., 1998, Pai *et al*., 1997, Petrella *et al*., 1997, Pickard *et al*., 2003, Kaplan *et al*., 1985, Stillman, 2000, Tsang and Hui-Chan, 2003) with results supporting an age-related decline in ability. For example, most recently Ribeiro and Oliveira (2010) compared knee joint position sense of young (average age 20.6 years) and older (average age 72.2 years) male participants and concluded the elderly group had double the error scores in joint position measurements than the younger group. An increase in knee joint position sense in elderly groups is further reported by Attwater *et al*., (1996), Pai *et al*., (1997), Petrella *et al*., (1997) Kaplan *et al*., (1985) and Hurley *et al*., (1998) despite the use of inconsistent joint position sense measurement techniques.

This apparent age-related decline can be attributed to changes in both peripheral and central levels (Ribeiro and Oliveira, 2010, Hurley, 1998, Horak *et al*., 1989). At peripheral levels,

there is evidence to suggest the dynamic response and the total amount of muscle spindles reduce with age (Miwa *et al*., 1995). Specifically, there may be a reduction in intrafusal fibres such as nuclear chain fibres and an accompanying increase in the spindle capsule thickness due to muscle denervation (Swash and Fox, 1972, Herter *et al*., 2014, Ribeiro and Oliveira, 2007, 2010, Shaffer and Harrison, 2007, Miwa *et al*., 1995, Mynark and Koceja, 2001). The changes in muscle spindle architecture may also be due to an increase in collagen and fibrous tissue content arranged in the inner capsule (Swash and Fox, 1972, Miwa *et al*., 1995). There is evidence to suggest the fibrous tissue encapsulating extrafusal muscle fibres thickens with age (Swash and Fox, 1972). In addition, nerve conduction velocity decreases and hence muscle spindle sensitivity decreases (Tanosaki, 1999, Mynark and Koceja, 2001) and the net number of mechanoreceptors serving a joint is reduced (Herter *et al.*, 2014, Aydoğ *et al*., 2006, Iwasaki *et al*., 2003) with ageing. Overall, there is evidence to suggest peripheral changes to the muscle spindle with age would be detrimental to joint position sense ability.

The central component of proprioception is also altered with ageing, there is a reduction in the dendrite system in the motor cortex and hence a reduction of motor neurones in the central nervous system (Ribeiro and Oliveira, 2010, Horak *et al*., 1989, Mynark and Koceja, 2001). The motor neurones that remain are larger and have a reduced conduction velocity (Campbell *et al*., 1973). There has also been anecdotal evidence of a reduction in grey matter and hence a less effective central nervous system (Scheibel *et al*., 1975, Herter et *al*., 2014). For a summary of all potential effects of ageing on proprioception see table five.

With all evidence considered it might be surprising a more obvious age-related reduction of knee joint position was not found in this thesis. However it is important to consider the potential limitations of the withstanding literature. Firstly, histological studies that suggest peripheral changes to various mechanoreceptors with ageing are indirect measurements of nerve function, typically from cadaver studies and therefore lack functional correlations. Further, the use of gold and silver chloride stains is not always accurate, vascular structures can be mistaken for mechanoreceptors, the classification of mechanoreceptors is also inconsistent and the identification alone of mechanoreceptors does not imply functionality (Johansson *et al*., 2000, McCloskey, 1978). It is possible architectural differences in older mechanoreceptors occur without functional changes. Secondly, there is not strong evidence to suggest changes to muscle spindles with age occur in all relevant muscles to joint position sense, the reductions in muscle spindle function could be muscle dependent (Shaffer and Harrison, 2007). As such, it is plausible muscle spindles which are not affected by ageing could compensate for the loss in

afferent information from other muscles. Indeed it is possible Type I muscle fibres remodel and regenerate lost Type II muscle fibres within damaged fibres to ensure continued effective movement (Faulkner *et al*., 2007). Indeed, this may well be why some research suggests age has no negative effects on static function or joint position sense (Mynack and Koceja, 2014).

Thirdly, there is very little evidence to suggest cutaneous, articular and Golgi-like or Golgi tendon organs are negatively affected by age (Ribeiro and Oliveira, 2007). Again, these fully functioning mechanoreceptors may compensate for the loss in some muscle mechanoreceptor function. Fourthly, another compensatory mechanism may occur in the central nervous system. It is possible peripheral deficiencies do occur in the muscle spindle with ageing and also central reductions in total number of neurones and grey matter. However, older adults may atone for the loss in the peripheral and central system by enhancing the sensitivity of central encoding of the remaining afferent information; this can be seen in studies examining attention and focus (Ribeiro and Oliveira, 2007, Meeuwsen *et al*., 1993). Herter *et al*., (2014) and Suetterlin and Sayer (2014) reported that elderly participants increased the attention given to motor tasks and hence central activity which may in turn attenuate the age-related decline in joint position sense. Finally, elderly people may have a reduced pain response due to a reduction in the grey matter processing capacity in appropriate pain regions (Quiton, 2007). Therefore, if testing of knee positions sensitises free-nerve endings, the elderly may not process this nociceptive afferent information and continue sensations of position (Quiton, 2007).

The results of this thesis demonstrated no obvious differences between the five age groups considered. However, knee extension position sense was positively correlated to age. This increase may be due to a combination of peripheral and central changes that may accompany aging. Clinical practitioners should use this information to inform proprioceptive treatment of elderly groups. It may be necessary to improve knee joint position sense to reduce the risk of injury. However, practitioners should not assume elderly or older age patients will have a proprioceptive deficit. Future work needs to consider how older age groups may make peripheral and central adaptations in order to compensate for age-related changes to proprioception.

5.2.3 The Effect of Activity Levels on Knee Joint Position Sense Measurement

The results of the current study indicate exercise levels (active, moderately active, moderately inactive and inactive), measured using the general practitioner physical activity questionnaire,

have no effect on knee joint position sense into flexion. This is contrary to the majority of previous research findings. However, exercise levels did affect JPS extension scores. In particular there was a significant difference between the active and inactive participants; active participants had lower absolute error scores by 1.3°. Correlation analysis revealed no relationship between Tegner activity scores and JPS flexion ability. Although there was a significant weak to moderate correlation coefficient between Tegner activity score and JPS extension ability (r= -0.321); as Tegner score increased (indicating a higher level of sports performance) absolute error score decreased. Therefore it would appear activity level may influence performance of knee joint position sense in to extension.

The majority of previous research reports that participation in regular physical activity improves knee joint proprioception ability (Ribeiro and Oliveira, 2010, Ribeiro and Oliveira, 2007, Petrella *et al*., 1997, Xu *et al*., 2004, Tsang and Hui-Chan, 2003, 2004). Ribeiro and Oliveira (2010) and Petrella *et al*., (1997) state populations who exercised three times a week for at least 45-60 minutes had improved knee joint position sense compared to non-exercisers. Elderly exercisers can achieve similar proprioception levels to healthy (but not necessarily active) young controls (Tsang and Hui-Chan, 2003, 2004). Research has also considered elderly populations and specific proprioception focused sports such as Tai Chi (for example Xu *et al*., 2004) and dancing (Schmitt *et al*., 2005). Tsang and Hui-Chan (2003) compared elderly Tai Chi practitioners to elderly activity based controls and found the Tai Chi group had significantly better knee joint proprioception. This is supported in work by Xu *et al*., (2004) and in addition this group compared elderly Tai Chi practitioners to an age-matched runners/ swimmers group and golfers and found no significant differences. Indeed there is some discussion as to whether specialised proprioception based exercise is the only type of activity to increase joint position sense. Schmitt *et al*., (2005) considered professional dancers and concluded they did not have heightened joint position sense when compared to more traditional exercisers. As well as sporting events, training programmes may also improve proprioception. Strength training (Thompson *et al*., 2003) and passive knee motion (Ju *et al*., 2011) has been shown to improve knee proprioception of both elderly and young healthy individuals. As has been demonstrated previously in this thesis, researchers used a range of proprioceptive measurements, which may explain any inconsistencies in research findings. However, it does appear exercise of any type may improve proprioceptive ability, not just exercise such as Tai Chi and dance.

Exercise may improve proprioception at both the peripheral and central levels (Hutton and Atwater, 1992). It is known that the total number of mechanoreceptors does not increase with exercise (Ashton-Miller *et al*., 2001). However, evidence suggests exercise reduces the loss of muscle spindle afferent ability which may occur during periods of sedentary behaviour (Ashton-Miller *et al*., 2001). Hutton and Atwater (1992) suggest regular exercise induces morphological adaptations at muscle spindle level, specifically reduction in the latency and increase in the amplitude of stretch reflexes. Furthermore, Petrella *et al*., (1997) explains exercise increases muscle strength which increases muscle control and hence proprioception ability, however this would obviously only be represented during active joint position sense testing. The repetition of a motor skill, as occurs in regular physical activity, can also increase the sensitivity of muscle spindle sensation and increase reliance of afferent information (Thompson *et al*., 2003, Ju *et al*., 2010, 2011) which again would improve proprioceptive acuity.

At the central level exercise may increase gamma motor neurone signals which in turn could increase muscle spindle sensitivity (Ashton-Miller *et al*., 2001). Ribeiro and Oliveira (2010) further suggest exercise affords the opportunity to make plastic changes in the central nervous system, which can improve the strength of synaptic connections among neurones. It is believed continuation of exercise into retirement ages creates a compensation for the loss of peripheral changes, such as reduced number of muscle spindles, by enhancement of sensitivity of the central encoding of sensory input (Horak *et al*., 1989). However, further research is required to substantiate these theories.

It is evident regular exercise could improve knee joint position sense, data from the current study provided support for this during knee extension results. However, there were no significant effects of exercise on knee flexion position sense. One possible explanation for this is the range of movement from 0° (unloaded) to a bent knee position is used less in sport and exercise than the extension movement from a bent knee to a midrange position commonly used in locomotion. Therefore physical activity may only enhance joint position sense in positions that are most commonly used in the movement. This raises an important methodological issue; joint position sense is a static measure of proprioception, but active or passive movement to that position cannot be avoided. Therefore, it may be incorrect to state the measurement of knee joint position sense is uniquely static, as it must always involve movement to and from the target position. This will be discussed further in the limitations section of this chapter.

A further issue to discuss is that the sample used in the current study may be representative of a more active population as it would appear even the participants over the age of 60 participated in some form of physical activity. The average Tegner scores for participants aged 60-74 years and 75 years and over were 2.5 and 2.2 respectively; this indicates participants were able to walk on uneven ground and participate in some physical activity. It should be noted here the Tegner scale has been shown to be reliable and valid and hence results can be trusted (Tegner and Lysholm, 1985). As previously discussed an increase in age can amount to a reduction in the number of motor units (Doherty, 1993), reduced excitability, cross-sectional area and fibre size and number of muscle mass (Vandervoort, 1992, Stalberg, 1989). For example by 80 years of age there is evidence to suggest the total number of muscle fibres will have decreased by 50% compared to a 50 year old (Faulkner *et al.*, 2007). Therefore it would be expected that older people have diminished proprioception. However, if older aged people continue or begin to participate in physical activity these muscle degeneration effects may be attenuated (Ribeiro and Oliveira, 2010) and muscle spindles may even be reinnervated by capturing neighbouring fibres that have become denervated (Vadervoot, 1992, Stalberg, 1989). This re-innervation of Type II muscle fibres to Type I fibres allow the cross sectional area to remain constant. Evidence further suggests potential reduction in the efficiency of the peripheral nervous system (muscle spindle) with age can be compensated for in the central nervous system; older people may enhance the sensitivity of central encoding of sensory information which has been reported as an increase in task attention (Ribeiro and Oliveira, 2007, Meeuwsen *et al.*, 1993) and hence reduce errors in position sense. Therefore, if the sample used in the current study were relatively active then joint position sense declines may have been mitigated by this activity. This may explain why knee joint position sense measures were not significantly different between GPPAQ groups; the sample did not include the required variation in physical activity to identify differences in knee flexion joint position sense.

Although, it is important to highlight, Briggs *et al.*, (2009) collected Tegner scores from 448 uninjured participants in the United States and in fact reported at average Tegner score of 4.6 for the over 60s age group. So, in fact, the current study may not represent a normal population. However, another possible explanation is that Tegner and GGPAQ scores are not sensitive enough to detect differences in all knee joint position sense measurements. Future research may consider the relationship between position sense and a direct measure of fitness such as a maximal aerobic test.

In conclusion, it appears exercise of any type may improve proprioceptive ability into knee extension, not just kinaesthetic exercise such as Tai Chi and dance. In fact, it may be that clinical practitioners should consider physical activity level as a more important proprioceptive variable than age (Rikli and Busch, 1986). This has important implications for clinical practitioners practice; it may not be necessary to introduce what has traditionally been known as specific "proprioceptive exercises" in training programmes but simply exercise of any type. Section 5.2 suggests there is not a "general proprioceptive ability" as such. Therefore, it may be more appropriate to include regular physical activity to improve proprioception ability. However there is still further work to be done on exercise and position sense ability to ensure the most effective programmes are implemented.

5.2.4 The Effect of Gender, Mass, Height and BMI on Knee Joint Position Sense Measurement

Results of this thesis revealed gender did not affect knee joint position ability for either flexion or extension. This is comparable to Hertel *et al*., (2006), Harriell *et al*., (2010) and Schmidt *et al*., (2013) whom also reported no gender effects on knee proprioception. A limitation of the current study is that hormone levels and menstrual cycle phases were not recorded from the female participants as part of the data collection phase. Therefore, the theory that menstrual hormones can affect proprioception cannot be disregarded. However, the standard deviations between men and women in each age group were very comparable (see Table 13); if a hormonal effect was present you might expect more variation in proprioceptive ability from the female participants due to the potential effects of the menstrual cycle. However, this does not to appear to be the case. Therefore, there is no evidence that men and women have different joint positions sense ability and hence clinical practitioners should not use different treatment practices for men and women.

There were some weak to moderate relationships between JPS into extension and height and BMI in the current study (see Section 4.1). One possible theory to explain the relationship between height and knee JPS into extension may be the length of the lever involved in knee extension. It would be logical to assume taller participants will have longer lower limbs; this would increase the torque produced (as torque = force x perpendicular distance from the axis of rotation) during knee extension (moving away from the axis into the mid-range target angle) compared to a shorter lower limb (assuming force is equal). This is turn may increase the "muscular sense" of the longer lever, indeed the mid-range target angle used in the knee JPS

extension protocol is within the range of maximum torque production. This may improve joint position sense. However, this is pure speculation and furthermore the correlation between knee joint position sense into extension and height was weak (r=-0.191) (Cohen, 1992); this cannot be attributed to an inadequate sample size as a power calculation was conducted prior to data collection. As such, this relationship may not be significantly relevant to clinical practitioners and practices should not be adapted dependent on height.

Joint position sense extension absolute error scores were also positively correlated to BMI. Paschalis *et al.*, (2013) considered the effect of BMI on knee joint position sense in three knee flexion target angles. Results revealed overweight (BMI>29kg/m^2) participants had significantly lower joint position sense ability. This may be attributed to muscle atrophy in overweight participants (Paschalis *et al.*, 2013) and a lower number of activated muscle spindles and hence reduced proprioceptive ability. Therefore, clinical practitioners may need to allow for some deficits in knee joint position sense when treating overweight patients. However, relationships do not provide cause and affect evidence; it may be the increased BMI was not the cause of the decrease in knee JPS scores. Furthermore, the relationship was only moderate at best (r=0.204) (Cohen, 1992). Again, it is recommended clinical practitioners do not modify their treatment based on BMI alone.

In addition, there was no relationship between JPS extension scores and mass or JPS flexion scores and any anthropometric data. The methods used in this study were reliable and valid. A sample size calculation also ensured the study had adequate statistical power. Therefore, we can be confident the results of this study can be generalised and used by clinical practitioners. This particular analysis provides evidence that mass, height and BMI may not be correlated to knee joint position. Therefore it may not be necessary to match control groups by mass, height and/ or BMI in future knee joint position sense research. Also, clinical practitioners do not need to modify their practice based on gender, height, mass or BMI.

5.2.5 The Effect of Self-reported Knee Condition on Knee Joint Position Sense Measurement

Participants in the normative sample were free from lower extremity injury. However, participants also completed a KOOS (knee injury and osteoarthritis outcome score) survey and a Lysholm survey to confirm they were truly free from lower extremity injury. Both scales have been shown to be valid and reliable (Collins *et al.*, 2011, Lysholm and Gillquist, 1982).

The current results of the self-reported surveys suggested some participants, although verbally stating they did not have a current injury prior to data collection, may have knee problems not diagnosed by a health care professional. Indeed, no age group presented an average KOOS score of 100 (no knee problems) and the lowest KOOS score across the sample was 26.8 (male aged 69 years) despite no clinical diagnosis. This is supported in work by Paradowski *et al*., (2006) who completed a large scale (N=568) KOOS survey and concluded age and gender affected KOOS scores. Furthermore, Paradowski *et al*., (2006) failed to report any age group with an average KOOS score of 100 (no knee problems). Similarly, no age group in this thesis data produced an average Lysholm score of 100 (no knee problems). This implies it may be difficult to collect data from a truly "uninjured" i.e. no pain, swelling, stiffness or soreness in the knee, population. The results of the normative study revealed significant weak to moderate negative relationships between JPS extension absolute error scores and KOOS and Lysholm scores, suggesting as knee problems increase JPS ability decreases.

Pai *et al*., (1997) compared threshold to detect passive motion in patients with knee OA to elderly and young control groups. Results suggested the OA group had worse knee kinaesthesia than the other two control groups; the OA may have caused mechanoreceptor damage in the knee joint which reduces joint proprioception. However, this research needs to be repeated with joint position sense measurements. In future joint position sense research it may be important to match groups by KOOS and/ or Lyshom scores in addition to age and activity levels. If an injured group is compared to an uninjured group, KOOS and/ or Lysholm may also be used to check the uninjured group have no undiagnosed issues.

5.2.6 Summary

Normative values of knee joint position sense across five age groups and both genders were provided in study three of the thesis. This normative data may be used by practitioners to evaluate rehabilitation programmes and also screen patients for proprioception imbalances and/ or deficits. The study also investigated the effects of knee direction, age, activity levels and knee condition on joint position sense. In this sample, direction of movement affected the measurement of knee joint position sense and hence practitioners should measure both knee flexion and extension. Age and BMI may also influence joint position sense ability. As age increases JPS extension absolute error scores decreased, and as BMI increased JPS extension

absolute error increased. Therefore, practitioners should match controls to age and BMI. However, it is important to consider the knee joint position sense protocol used in this thesis measured the conscious outcome of afferent and efferent signals. There is no evidence to confirm a strong link between conscious and unconscious proprioception. It may be more sensitive protocols are necessary to identify the unconscious differences in peripheral and central commands in an individual in future studies.

5.3 The Effect of Injury on Knee Joint Position Sense Measurement

5.3.1 A Non-Athletic ACL population

Two reviews on the risk factors of lower extremity injuries did not include joint proprioception (Neely, 1998, Murphy *et al*., 2003). This demonstrates researchers may not consider proprioception deficits are an important injury risk factor. However, data from study four of this thesis, suggests ACL deficient patients do have reduced joint position sense ability and hence it is important clinicians consider proprioception aspects in rehabilitation programmes. Specifically, ACL patients had knee joint position error approximately 60% higher than uninjured knees and external controls. Many researchers have provided evidence to support knee joint position sense deficiency following ACL injury (Bonfim et al., 2003, Roberts et al., 2000, Rehm et al., 1998, Barrett 1991a, Carter et al., 1997 Corrigan et al., 1992, Ochi et al., 1999, Katayama et al., 2004, Baumeister et al., 2008). However, the majority of previous research measured knee proprioception using protocols that were potentially unreliable and not validated. Therefore, the current study is the first to provide evidence of a joint position sense deficit following ACL injury.

Over the last three decades authors have increasingly supported the notion that ligaments only play a supplementary role in proprioception (Burke *et al*., 1988). However, results of this thesis on ACL patients and knee joint position sense report the anterior cruciate ligament may provide more important primary afferent information. Articular receptors in the ACL can contribute to joint position sense of the knee (Johansson *et al*., 2000). The loss of these receptors following injury is thought to cause a deficit in the sensory information provided for accurate static proprioceptive ability (Marks *et al*., 2007, Barrack and Munn, 2000). ACL injury is also associated with menisci damage within 73% and 98% of patients (Marks *et al*., 2007). This can result in increased knee laxity and potentially poorer proprioceptive ability (Roberts *et al*., 2004a). The results of this thesis suggest mechanoreceptors in the surrounding knee muscles

and adjacent joints are unable to compensate for the loss of ACL afferent input. It may well be the afferent information transmitted following an ACL injury is non-physiologically organised during the ensemble coding procedure and hence the central nervous system cannot process this information as accurately as pre-injury status (Marks *et al*., 2007).

An interesting finding was patient's uninjured limb had better knee joint position sense than external controls. Previous research has indicated the opposite to this finding; the contralateral limb of ACL patients having poorer knee proprioception than external controls (Arockiaraj *et al*., 2013). The improved ability in the contralateral leg in patients may be attributed to a training effect during rehabilitation. ACL injury rehabilitation may be focused on muscle strengthening and improved sensorimotor ability around the knee joint. The uninjured leg would therefore achieve muscle hypertrophy around the uninjured knee and perhaps increase muscle spindle activity and hence increase knee joint position sense. This may also be explained by compensation techniques used by ACL deficient patients. Due to a reduction in trust on the deficient side, patients subconsciously train the uninjured limb to dissipate higher loads during movements such as landing and gait and hence increase muscle tone on the uninjured side which in turn may increase proprioceptive ability.

In summary clinical practitioners can now be more confident of a joint position sense deficit following ACL injury. This increase in position error appears to be 60% higher than uninjured knees. Therefore, it is important practitioners continue to develop rehabilitation programmes that aim to improve position sense in specific joints. However, it is not yet known how functionally significant this deficit would be to patients. Section 5.7 discusses this important point in more detail.

5.3.2 An Elite Athletic ACL population

It has been suggested that non-injured elite or high performing sports athletes have a heightened proprioceptive ability (Safran *et al*., 2001, Lephart *et al*., 1996, Barrack *et al*., 1984a, 1984b, Euzet and Gahery, 1995, Muaidi *et al*., 2009, Kiefer *et al*., 2013, Han *et al*., 2013, Waddington *et al*., 2013, Lin *et al*., 2006, Courtney *et al*., 2013). This may be because of innate characteristics that predispose them to participation in elite levels of sport (Euzet and Gahery, 1995) and/or development of muscle spindles and central processing following long term training (Ashton-Miller *et al*., 2001). Despite this, it is clear from the plethora of literature available on athletic populations that athletes (even at the elite level) experience ACL injury

and may maintain a proprioception deficit even after rehabilitation causing secondary injuries (Ribeiro and Costa, 2001, Kamath *et al*., 2014). However, there is limited research on knee proprioception measures of elite athlete's following ACL injury and repair.

Results of study 4.2.1 indicate that elite athletes with previous ACL injury had reduced knee joint position sense in both flexion and extension when compared to external controls and their contralateral knee. Therefore, elite athlete's increased proprioceptive ability may not predispose them from ACL injury, or not all elite athletes have higher proprioceptive acuity compared to controls. Stillman *et al*., (1999) reported no differences in knee joint position sense between elite Australian Rules footballers and non-athletic controls. As with the majority of injury-related studies, all data in this thesis is retrospective and therefore it is impossible to select the correct explanation for ACL injuries to elite athletes. Of course, injuries are multi-factorial, so it may be another factor is the main cause. For example Wojtys and Huston (2000) reported muscle strength to be significant risk factor of ACL injury. Also, the knee joint has visco-elastic properties during physical activity; therefore knee laxity is known to increase with participation in sport (Dieling *et al*., 2014). For example, Nawata *et al*., (1999) demonstrated an increase in knee laxity following acute bouts of exercise that persisted up to 120 minutes after the task. This is supported in earlier work by Skinner *et al*., (1986b); exercise increases knee joint laxity which may reduce proprioceptive ability. Synthesis of this evidence on elite athletes provides a potential explanation for the continued rate of ACL injury in sports; firstly, if athletes do have an increased proprioceptive acuity, this may become reduced by the increase in knee laxity. Secondly, if some elite athletes do not have a heightened proprioceptive ability, an increased knee laxity could potentially reduce proprioceptive levels below normal non-exercising people. Either way both theories will result in an increased risk of knee injury.

It should be stated that there has been some acknowledgement of variability in the neuromuscular control in athletes. Indeed clinical practitioners will be aware of the so called "copers" and "non-copers" of ACL injuries (Herrington and Fowler, 2006). An athlete with an ACL knee injury can either continue participation in their sport, even at an elite level, or require almost immediate surgical reconstruction. Clinical practitioners should use the recommended measurement technique in this thesis to identify athletes with higher than average (>5°) knee joint position sense error. It may be these athletes are the "non-copers" and hence should be monitored closely. Furthermore, following ACL injury there appears to be a 60% increase in joint position sense error. Clinical practitioners need to consider the functional applications of this in future studies.

Results of the current study indicate elite athletes' contralateral leg was no different to the external controls. In the non-athletic population the contralateral leg was actually better than external controls. It may well be that non-athletic populations improve JPS in the uninjured knee as they undergo intense rehabilitation and have no loss of articular mechanoreceptors, but also may be compensating more for the injured leg. Whereas the elite athlete's contralateral leg may not need to compensate as much as the injured leg may have better proprioception compared to the non-athletic group. Also, we compared elite athletes to a non-elite athletic external control group which is a limitation of the study design.

Unfortunately, elite athletes for whatever reason are still at risk of ACL injury. This thesis provides evidence of a reduced knee position sense following ACL injury using a reliable and validated protocol. Therefore, preventative measures should be included in training programmes. However, as yet, it is unclear what preventative measures should involve. Future research must research appropriate exercises that are site specific and evaluate these using reliable and valid measurements as provided in this thesis.

5.3.3 The Effect of Additional Injuries on Knee Joint Position Sense Measurement

Study 4.3 provided a small mixed-group population of participants with a variety of knee injuries not including anterior cruciate damage. The injuries reported in this sample included early stage OA, patellofemoral pain syndrome, patella re-alignment, knee laxity, cartilage and/or menisci damage and tibial surgery. Results of this study indicated knee injuries other than ACL damage may not reduce position sense ability in to either flexion or extension compared to age and activity level matched controls. The injured group differed to the control group by only 0.3° and 0.1° for knee flexion and extension respectively. In addition, standard deviations which may be used as an indication of variability (Field, 2005), were similar between the injured and control groups for both knee flexion error scores (mean difference of 0.29°) and extension error scores (mean difference of 0.23°). Therefore the distribution of average error scores appeared to be unaffected by the range of knee injuries in the patient group compared to the normal variability levels in the uninjured group. There does not appear to be any secondary research on the effects of tibial surgery on knee proprioception. However, the sections that follow will discuss how knee injuries may or in this case may not affect knee static proprioception.

Research highlights a decline in proprioceptive acuity following knee injuries other than ACL damage. The largest area of research is in proprioception and knee osteoarthritis. There is evidence to suggest dynamic proprioception (threshold to detect passive motion) is reduced in OA patients (Pai *et al*., 1997, Sharma *et al*., 1997, Koralewicz and Engh, 2000, Collier *et al*., 2004, Lund *et al*., 2008, Hewitt *et al*., 2002, van der Esch *et al*., 2007, 2013, Cammarata *et al*., 2011, Chang *et al*., 2014, Sanchez-Ramirez *et al*., 2013). There has also been evidence to suggest joint position sense (static proprioception) reduces in OA patients (Garsden and Bullock-Saxton, 1999, Hurley *et al*., 1997, Mohammadi *et al*., 2001, Marks *et al*., 1993, Barrett *et al*., 1991b, Hassan *et al*., 2001, Bennell *et al*., 2003, Segal *et al*., 2010, Felson *et al*., 2000, Sanchez-Ramirez *et al*., 2013, Hurley, 1997). This decline in proprioceptive ability has been attributed to impaired articular receptors in the involved knee, a reduction in gamma motor neurone activation and reduced sensitivity in muscle spindles, inflammation and effusions and concomitant injuries to other knee tissues (Knoop *et al*., 2011, Lund *et al*., 2008). Therefore, a reduction in knee proprioception was predicted in the current study, but this was not the case.

In contrast, Hall *et al*., (2006), Lund *et al*., (2008) and Bayramogku *et al*., (2007) failed to find any differences in JPS between OA patients and external controls which is similar to the result of the current study. Therefore, it is possible OA patients do not have static proprioception deficits due to the degeneration of knee tissues and effusions caused by the disease. It is plausible patients are able to compensate, perhaps via increases in muscle afferent input and central nervous system attention, and keep knee joint position sense similar to asymptomatic controls. It may also be the tissues that are most affected by knee OA do not play a primary role in knee joint position sense (such as menisci) and furthermore the potential benefits of articular afferents may have already been lost with age (Simmons *et al*., 1996, Attfield, 1996). Indeed there is evidence to suggest following total knee arthroplasty and knee replacement surgery in which large sections of tissue are completely removed, patients do not demonstrate a reduced static proprioceptive ability (Buz-Swanik *et al*., 2004, Attfield *et al*., 1996, Cash *et al*., 1996). Patients' knee JPS may even improve following surgery (Isaac *et al*., 2007, Ohuchi *et al*., 2014, Attfield *et al*., 1996). The surgical techniques used in total knee arthroplasty or replacement may preserve mechanoreceptors in tissues such as the capsule, ligaments, fat pads, and perimeniscal tissue, promote regeneration of the sensory afferents and help modify protective reflex arcs but adjusting capsular tension (Safran *et al*., 1994). These considerations can reduce the pain and inflammation in the joint and restore the capsule joint space and along with an improvement in daily living and physical activity levels can actually improve

proprioception. However, there is also evidence that suggests surgical treatment impairs knee proprioception (Ishii *et al*., 1997, Pap *et al*., 2000, Weiler *et al*., 2000). Clinical practitioners should therefore be aware that some OA patients may benefit proprioceptively from surgery, whereas some patients may cope with OA (as appeared to be evident in this thesis) and will not need surgery.

It is important to consider the error score values from the supporting literature. Hall *et al*., (2006) reported knee JPS error scores between 5° and 6.5° in their OA patients using a similar method to the current study; but failed to include a control group. As the contralateral leg may also be affected by OA (Sharma *et al*., 1997) it is difficult to conclude that OA did not decrease JPS acuity. Lund *et al*., (2008) reported JPS error scores between 5° and 6° in OA patients and 4.6° and 6.5° in matched external controls using an active-active replication protocol using electrogoniometery. Furthermore, Bayramogku *et al*., (2007) reported even greater error scores between 4°and 9° in OA patients and 5° and 8° in matched controls using an IKD passive-passive protocol. These ranges of knee JPS are higher than reported in the current study (range between 2.8° and 3.7°). Obviously, the reported studies only include OA patients, whereas the current study included all non-ligament knee injuries and therefore the effect of OA may have been masked by other knee injuries. However, standard deviation scores do not support this notion. The severity of OA in the current study was only early stage (Kellgren/Lawrence scale Grade 1 – minimal degenerative joint disease), so again the reduction in JPS ability may have been less evident. However, the external control groups in Lund *et al*., (2008) and Bayramogku *et al*., (2007) also had increased knee JPS than the current study, in some cases more than double. This may be due to the sensitivity of the protocols; Bayramogku *et al*., (2007) used a passive-passive protocol, thus eliminating much of the afferent information that is contributed by muscle spindles and hence decreasing position sense. The reliability and validity of JPS measurement was not reported in literature and therefore the higher values could be due to increased measurement error. The results of the current study were taken using a reliable and validated technique; therefore future studies may use this method when collecting OA patient JPS data. An additional problem with research in this area may be that external control groups are aged matched and thus these participants may also have degenerative knee JPS caused by other age related declines that are not clinically diagnosed (see section 5.2.2).

Indeed, there is no evidence to support correlations between OA and functional performance measures (Marks *et al*., 1993, Bennell *et al*., 2003). The most significant predictor of OA progression may be BMI and maximum voluntary quadriceps contraction not proprioception

(Hassan *et al*., 2001, Segal *et al*., 2010). Although, this thesis provides some evidence of weak to moderate correlations between knee JPS into extension and Lysholm and KOOS self-reported scores. Therefore research into OA and knee conditions and joint position sense is warranted in the future.

Patellofemoral pain syndrome (PFPS) is a painful and unfortunately common injury in physically active people (Baker *et al*., 2002). As with OA patients there is evidence to suggest this knee problem will decrease static proprioceptive ability. In both weight bearing and non-weight bearing conditions PFPS patients demonstrate poorer knee joint position sense than age and physical activity matched controls (Baker *et al*., 2002, Callaghan *et al*., 2008). This difference was attributed to the abnormal tissue stresses caused by an increase in the lateral tracking of the patella in PFPS patients (Callaghan *et al*., 2008). This could potentially "dis-organise" the afferent signals at the peripheral level and create abnormal motor control patterns (Callaghan, 2011). However, research into PFPS is relatively scarce compared to OA and ACL injury and hence it would perhaps be premature to conclude PFPS does induce proprioceptive declines in all patients. Indeed in the current study no differences were found between knee injury patients including those with PFPS and matched controls. Further, Naseri and Pourkazemi (2012) failed to find a reduction in weight bearing and non-weight bearing knee JPS in PFPS patients when matched to controls. This could be due to the severity of the syndrome, it may well be, as with OA, greater severity of the knee disorder increases the proprioceptive problem (Naseri and Pourkazemi, 2012). As the syndrome is most common in physically active people, it could also be that this population have a heightened proprioceptive ability (see section 5.2.3) and the injury simply reduces their ability to the normal asymptomatic population. Alternatively, Callaghan (2008) proposes the argument for "copers" and "non copers" with knee injury. He states some PFPS may be able to "cope" with the injury by using the brain's plasticity possibilities; the central nervous system is able to adapt and compensate for the misalignment of the patella whilst others are unable to "cope". Clinical practitioners again as with OA patients cannot be overly confident in presuming patients with knee injuries, in this case PFPS, will have a proprioceptive deficit. Until a large scale study using the reliable and validated method of knee joint position sense is completed, it is unclear if practitioners need to focus specifically on this in rehabilitation. However, if any patient presents with knee JPS above 5°, it perhaps be advisable to monitor this patient more closely.

Patella misalignment could also cause knee proprioceptive deficiencies (Jerosch and Prymka, 1996) although there have been limited investigation into this area. Correlated to patella

misalignment is the effect of knee laxity on proprioception, which has been discussed in previous sections (see 5.3.1 and 5.3.2). Briefly, an increase in knee laxity can cause abrupt movements of the joint, which may alter ligament afferent signals and disrupt knee proprioception (Sharma, 2004). However, again there is very little evidence to support this theory in symptomatic populations (Smith *et al*., 2014). Recently, Smith *et al*., (2014) did report only minimal loss of joint position sense ability in patients with recurrent patella dislocations and consequently medial patellofemoral ligament reconstructions. Thus, this patient group may not have reduced static proprioception and clinical practitioners may therefore not need to prescribe specific proprioceptive exercises in rehabilitation programmes.

Cartilage and meniscal injuries are some of the most common knee injuries in physical activity (Diaz, 2013). As discussed in chapter two; there is evidence to suggest there may be mechanoreceptors in the cartilage and menisci of the knee. The medial meniscus may contain more mechanoreceptors as it is attached to both ligament and capsule whereas the lateral meniscus is attached only to ligament (England *et al*., 2009). Therefore it follows that again damage to these structures would alter the afferent information relayed to the central nervous system which may disrupt proprioceptive signals. However, this theory was not supported in the current study; knee static proprioception was not reduced in a mixed knee injury group compared to controls. Therefore, it may be tentatively concluded meniscus and cartilage tears are not significant enough alone to disrupt proprioception.

The pain and possible inflammation induced through any knee injury would increase the afferent discharge from the small diameter type III and type IV (pain) receptors and thus potentially dis-organise neuromuscular control about the knee joint and cause abnormal proprioception responses (Baker *et al*., 2003, Capra and Ro, 2000). However, there is a lack of evidence to support the notion that pain in fact increases joint position sense error. Indeed Bennell *et al*., (2005) reported no decline in knee JPS when the joint was injected with hypertonic saline to induce pain. This suggests pain within the joint may not alter static proprioception alone; it is plausible the muscle and central nervous system can adjust to this pain accordingly (Bennell *et al*., 2005). However, although not the focus of this thesis, the individuality of pain pathways and pain thresholds and the correct method to measure pain are still not clearly understood. Therefore, clinical practitioners should acknowledge this in practice. Furthermore, practically all knee injury related research is retrospective; therefore it is impossible to study if the injury was caused by or is the cause of knee proprioceptive decline. This should be addressed using longitudinal research designs in the future.

5.3.4 Summary

In a recent injury survey into high level athletes (National Collegiate Athletic Association division 1) ACL injuries were reported as still a worrying and potentially career ending injury (Kamath *et al*., 2014). Therefore, it is imperative clinical practitioners are aware of any potential risk factors to this injury. This thesis presents evidence for knee joint position sense as one of these potential factors. Further, once ACL damage is acquired, if the severity of the injury increases, proprioception ability may decrease (Glencross and Thornton, 1981). Thus practitioners should use the method stated in this thesis to both pre-screen athletes and evaluate rehabilitation programmes prescribed to athletic patients.

Contrastingly, the cluster sample of other knee injuries did not demonstrate a reduction in knee joint position sense. These injuries included early stage OA, patellofemoral pain syndrome, patella re-alignment, knee laxity, cartilage and/or menisci damage and tibial surgery. Therefore, from these initial findings it may be suggested any injury that does not damage a knee ligament, may not cause a JPS deficit. It is possible the damage to alternative structures is compensated for by other mechanoreceptors in and around the joint. However, in future studies larger samples of each injury should be considered to validate these findings.

5.4 The Effect of Fatigue on Knee Joint Position Sense Measurement

It has been suggested that fatigue induces changes to both the peripheral and central processing of sensory information. One theory suggests motor units become desensitised in conjunction with a fatigued state (Rozzi *et al*., 2000, Paschalis *et al*., 2007, 2008, Ribeiro *et al*., 2008, Hiemstra *et al*., 2001, Hutton and Atwater, 1992, Lattanzio and Petrella, 1998, Fortier and Basset, 2012, Gregory *et al*., 2004, Hutton and Nelson, 1985, Djupsjöbacka *et al*., 1994, Hayward *et al*., 1991) and therefore joint position sense becomes less accurate. Further, the motor unit may become less efficient due to a reduction in the number of functioning sarcomeres in damaged muscle fibres and / or muscle acidosis and associated metabolites (Fortier and Bassett, 2012, Skinner *et al*., 1986a, Skinner *et al*., 1986b, Lattanzio *et al*., 1998, 1997, Changela *et al*. 2012, Ribeiro and Oliveira, 2011, Hayward *et al*., 1991). The release of fatigue induced metabolites also appears to modify the gamma-motor neurone and gamma-alpha co-activation pathways (Hutton and Nelson, 1985, Fortier and Bassett, 2012) which negatively affects the motor control of movement (Roberts *et al*., 2004b). Fatigue may also increase joint laxity and again disrupt the central processing of afferent information (Changela

et al., 2012, Roberts *et al*., 2004b, Skinner *et al*., 1986a, 1986b). Additionally, an increase in pain during fatigued states can induce nociceptor activation (Type III and IV afferents) and reduce motor cortex excitability (Ju *et al*., 2010, Fortier and Basset, 2012).

However, in spite of these theories study 4.4 reported knee joint position sense did not reduce following an individualised local peripheral fatiguing protocol. In fact, positional errors into knee flexion and extension reduced by 0.17° and 0.14° for flexion and extension directions respectively after fatigue. These values are well within the corresponding standard error of measurement values. Other research has also failed to find a main effect of fatigue on knee proprioception (Rozzi *et al*., 1999b, Bayramoglu *et al*., 2007, Skinner *et al*., 1986a, Miura *et al*., 2004, Stillman *et al*., 1999, Marks *et al.*, 1993, Dieling *et al*., 2014). Therefore, peripheral muscular fatigue may not be able to reduce proprioceptive ability and thus it may not be a reduction in joint proprioception that increases the risk of injury with fatigue (Hiemstra *et al*., 2001). However, a complementary theory to explain the results regards the fatiguing protocols; were the methods used actually able to produce a fatigued *proprioceptive* state? The neuromuscular system is highly adaptable to changing states such as fatiguing (Enoka and Stuart, 1992) and Burgess *et al*., (1982) states the fusimotor system appears to be relatively fatigue resistant. Furthermore it is unclear whether intrafusal muscle fibres can be driven to fatigue in the same way as extrafusal muscle fibres. Indeed, Hutton *et al*., (1992) demonstrated that intrafusal muscle became stiffer during fatiguing due to the persistence of actin and myosin binding and hence may enhance proprioceptive information. Hutton *et al*., (1992) also predicted static proprioception (JPS) would not be affected by fatigue as Ia and II sensitivities were relatively unchanged by fatigue. In addition other mechanoreceptors such as those situated in the Golgi-tendon organ, joint capsule and skin may in fact increase in sensitivity with fatigue and potentially compensate for any loss of afferent muscle spindle information (Hutton *et al*., 1992). Adjacent joints and their included muscle groups could also potentially compensate for the loss of peripheral information from the affected fatigued joint (Hunter *et al*, 1992) as would happen in kinematics of movement during a musculoskeletal injury.

It is also important to consider the central modifications that occur during fatigue (Noakes, 2012); isolated peripheral or muscular fatigue to knee flexor and extensor muscle alone may not significantly impose a central fatigue affect. Central fatiguing has been defined as "…*an unwillingness to activate the motor pathway to the extent expected, anticipated or required to perform the task*" (Macintosh and Rassier, 2002, p.43). Thus if central fatiguing did not occur in proprioceptive pathways it may be that central processing of afferent information remains

effective and even potentially compensatory (through increased attention to the task (Ashton-Miller *et al*., 2001) and/or activating progressively greater numbers of moto-neurones and /or by increasing their discharge rate) following the fatiguing protocol (Noakes, 2012, Lorist *et al*., 2002) . Evidence even suggests muscle spindle discharge increases and hence the gain in motor neurone discharge is increased during initial fatigue to activate muscles more strongly and keep force production consistent (Hutton *et al*., 1992). It is plausible intrafusal muscle fibres do not fatigue until the later stages, once the extra-fusal fibres have declined. Thus, it may not be possible to "proprioceptively" fatigue one joint using peripheral fatiguing protocols such as isokinetic dynamometry alone due to the various potential compensatory mechanisms (i.e. adjacent mechanoreceptors and central processing modifications) and difficulty in reducing intrafusal spindle performance. A torque or force production may reduce after peripheral/muscular fatigue but proprioception may well stay constant, further there is no evidence of relationship between strength force production and proprioception (Enoka and Stuart, 1992). A peripheral fatiguing protocol was used in this thesis to keep the focus isolated on the knee joint alone as is consistent with all the previous thesis' studies. However, it would appear researchers should possibly reconsider the use of this type of fatiguing task if considering its effect on static proprioception.

This has been supported in research that considered more global procedures to fatigue such as cycling, running and match simulation (Roberts *et al*., 2004b, Bayramoglu *et al*., 2007, Lattanzio *et al*., 1997, Changela *et al*., 2012, Baharlue and Khayambashi, 2012, Miura *et al*., 2004, Skinner *et al*., 1986a, Ribeiro *et al*., 2008). These protocols aimed to incorporate tasks that fatigue mechanoreceptors across multiple joints and the central nervous system. The majority of findings indicated a reduction in knee proprioception ability following the fatiguing protocol. Miura *et al*., (2004) attributed this reduction to a reduction in the efficiency of the central nervous system that reduced the precision of motor control and hence interrupted stabilising and controlling activities about the joint.

The role of the central nervous system in fatigue is a relatively recent area of investigation (Taylor and Gandevia, 2008) as the more distal affects in the periphery have been the main focus for researchers. Recently, it has been suggested if central fatigue occurs there will be progressive supraspinal fatigue, changes in excitation and / or inhibition and potentially a reduced gain (the receptor output firing rate / magnitude of the input stimulus) at the motor neuron pool (Taylor and Gandevia, 2008). However, it has also been proposed that peripheral

or muscular fatigue is governed by the central nervous system; the central components do not allow peripheries to become fully fatigued (Noakes, 2012) and in fact only allow a maximum of 60% of muscle mass to become activated during prolonged exercise (Sloniger *et al*., 1997a, b). This prevents the system from ever completely failing (Noakes, 2012). Further studies should investigate how central fatiguing affects joint proprioception. This has been completed to some extent in research on fatigue "sensation" or the sense of force (Enoka and Stuart, 1992, Enoka *et al*., 2011). This sensation is defined as the "…*perceived effort associated with a task...derived from centrally generated motor commands that give rise to corollary discharges*" (Enoka and Stuart, 1992, p1643). Fatigue may in fact be seen as a centrally driven sensation and this sensation may actually improve joint position sense (Noakes, 2012). Indeed Noakes (2012) states the effects of fatigue both begin and end in the brain. This will be discussed in more detail in section 5.6.

In summary, results from the current study can inform clinical practitioners in two ways. Firstly, peripheral muscular fatigue may not induce static proprioceptive deficits; there was no main effect of fatigue on knee joint position sense. However, secondly, the peripheral muscle fatiguing protocol may not in fact induce *proprioceptive* fatigue. The actual measurement of the effects of peripheral muscular fatigue continues to focus on muscle contractile properties such as maximum torque output. However, this may oversimplify the processes involved in motor control. The measurements do not yet accurately consider central processes and may be oversimplified (Noakes, 2012). Furthermore secondary mechanoreceptors and central processing can adapt and compensate for the decline in extrafusal muscle damage and intrafusal muscle spindles may be relatively fatigue resistant. Future studies should consider central fatiguing using the reliable and validated knee joint position sense measurement technique identified in this thesis.

5.5 Clinical and Functional Relevance

This section will firstly discuss the clinical relevance of the reported joint position sense measures and link this to potential rehabilitation programmes. Secondly, it will explore the functional relevance of proprioception.

The concept of proprioceptive exercises in rehabilitation programmes has been applied to a wide range of neurological, orthopaedic, arthritic and post-traumatic sport-related disorders (Stillman, 2000). However, the clinical significance of knee joint position sense data can be

considered in the context of the reported measurement errors in the reliability studies conducted in the thesis. Two knee joint position sense protocols are recommended in this thesis (see section 3.5). Both had excellent test-retest reliability (Cohen, 1992). However, other measurement error results are not quite as favourable. The standard error of flexion measurement was 0.4° and the standard error of extension measurement was 0.6°. This is equal to between 9% and 13% of the normative flexion error scores and 14% and 26% of extension error scores. Furthermore, in rehabilitation programmes it is also important to acknowledge the smallest detectable difference to ensure improvements are not masked by measurement error; for knee flexion the smallest detectable difference was 1.1° and for knee extension was 1.67°. If we relate these values to the normative values reported in study 4.1 it is apparent that the smallest detectable difference could constitute between 26% and 37% of the total absolute error score into flexion and 39% and 73% of the total absolute error score into extension. Clinical practitioners working in a pre-habilitation setting with uninjured normative participants would therefore potentially need to increase static proprioceptive performance by up to 73% of the patient's current status to see a clinical improvement.

It also follows that the statistical differences between ACL injured patients and their contralateral leg or external control groups may not have clinical relevance. Data from this thesis reveal knee joint position sense absolute error scores normally range from 2.3° to 4.3° in uninjured populations. A static proprioceptive error score of over 5° is thought be the minimum to indicate a clinically important difference (Callaghan *et al*., 2002 Burgess *et al*., 1982). ACL patients from a non-athletic population had an average error score of 7.9° for the injured knee; this is between 3.5° and 5.6° higher than the normative data group. This difference is greater than both the standard error and smallest detectable difference for this measurement. Similarly elite athletes with an ACL injury had an average error score of 8.1° and 7.2° for knee flexion and knee extension respectively for their injured knee. Again, these values produce differences compared to the normative sample that are greater than the reported standard error of measurement and smallest detectable differences for the measurement protocol.

Previously the magnitude of static proprioceptive abnormality necessary for a clinically discernible disturbance of functional knee capacity was unknown (Baker *et al*., 2002). However, both ACL groups had static proprioception scores above 5° and these values were taken using a reliable and valid tool. Therefore, this gives support to the previously arbitrary threshold for "poor ability" (Callaghan *et al*., 2002, Burghess *et al*., 1982). Clinical

practitioners may now be confident that ACL injury does reduce static proprioceptive ability. Thus, rehabilitation programmes may need to focus on improving this ability. Indeed a number of studies state proprioceptive training is an essential element of rehabilitation (Beard *et al*., 1994, Caraffa *et al*., 1996, Cerulli *et al*., 2001, Lin *et al*., 2009, Soderman, 2000, Laskowski *et al*., 2000, Hewett *et al*., 2013, Swanik *et al*., 1997).

Cerulli *et al*., (2001) define proprioceptive training as "…*a series of exercises or situations that will elicit a response from the central nervous system in order to counteract external stimuli*" (p.636). Furthermore, Swanik *et* al., (1997) states rehabilitation of proprioception ability must include four key steps; proprioceptive and kinaesthetic sensation, dynamic joint stability, reactive neuromuscular control and functional movement patterns. Examples of exercises included in proprioception rehabilitation programmes include balance training and closed kinetic chain exercises such as a single leg hops (Laskowski *et al*., 2000, Swanik *et al*., 1997). These cause compressional loads in the knee and therefore it is believed to maximally stimulate articular mechanoreceptors as well as muscle spindles which may improve their function (Swanik *et al*., 1997).

Clearly, clinical practitioners are aware of the importance of re-establishing proprioception after an ACL injury, but it is still unknown how and if rehabilitation exercises do in fact improve proprioceptive ability. Indeed there appears to be very little evidence "proprioception exercises" such as "wobble" and balance board tasks do actually improve proprioceptive ability (Stillman, 2000, Ashton-Miller *et al*., 2001). There is some limited evidence that ankle proprioception improves following wobble board training (e.g. Waddington and Adams, 2004). Also Hurley and Scott (1998) reported knee joint position sense improvements in OA patients following five weeks of rehabilitation. However, the programme included strength training, cycling and functional training as well as "proprioceptive" balance board tasks and as such it is impossible to conclude which aspect resulted in the increase in knee JPS. Friemert *et al*., (2006) did provide evidence that continuous active motion movements improve knee joint position sense following ACL reconstructive surgery. However, again this exercise may not be seen as a true "proprioceptive" exercise. Joint position sense may also be improved if both visual and proprioceptive feedback is provided during the rehabilitation programme (Brindle *et al*., 2009). Although, it is clear these rehabilitation exercises can also improve muscular strength around the injured joint (e.g. Lin *et al*., 2009). Indeed, most clinical practitioners include more than only proprioception exercises into rehabilitation (Ingersoll *et al*., 2008, Swanik *et al*., 1997). These include strengthening, reflex-training and neuromuscular

activation patterns. Much of this would also help improve proprioception. Therefore, it is very difficult to attribute any potential proprioception improvements to the appropriate component.

Clinical practitioners must remember balance is not synonymous with proprioception. It is also important to acknowledge balance based exercises may not be true tests of proprioception (e.g. Westlake and Culham, 2007, Perrin *et al*., 1999) as vestibular and visual systems are involved in this motor task (Ashton-Miller *et al*., 2001). Balance tasks may not in fact improve proprioception rather distribute more dependence to the visual and vestibular systems (Paillard and Brouchon, 1974, Brindle *et al*., 2009). Furthermore, Ashton-Miller *et al*., (2001) and Meeuwsen *et al*., (1993) propose balance training may not actually modify afferent information from the peripheral areas but more improve attention given by the CNS to the tasks and this improve central processing of the relayed afferent information. It is unclear if balance tasks modify the sensory or motor aspects of balance ability (Ashton-Miller *et al*., (2001). Furthermore, it is suggested balance ability is highly variable and unreliable (Brouwer *et al*., 1998), another reason not to use this measurement as an indication of proprioceptive ability.

Previous research investigating the effectiveness of proprioceptive exercises is the evaluation techniques; either the evaluation is completed using static and dynamic proprioception tests that have not be checked for reliability and validity (Cooper *et al*., 2005) or the evaluation does not include specific proprioceptive measures such as JPS or TTDPM (Ashton-Miller *et al*., 2001) and/or the evaluation is the on the number of acquired injuries before and after the intervention (Soderman *et al*., 2000, Hewett *et al*., 1999, Caraffa *et al*., 1996). The latter issue has obviously limitations; injury occurrence is multi-factorial and hence this variable alone cannot identify any potential changes caused by the proprioceptive exercises. However, this does not mean proprioceptive exercises within rehabilitation programmes do not have an impact on proprioceptive ability especially since there is now strong evidence for sensorimotor plasticity and proprioceptive learning (Ostry *et al*., 2010). Indeed in earlier research Laszlo and Bairstow (1983) proposed children's kinaesthetic sensitivity (measured using drawing tasks) can be improved providing their kinaesthetic awareness had been established during training. It may well be researchers as yet are not using the correct evaluation tools and/or proprioceptive exercises to optimise a potential cause and effect. The complex interactions and relationships between the individual components of the sensorimotor system make it very difficult to evaluate specific improvements of one of these components following rehabilitation.

If a proprioception deficit is present in some people, it is unknown as to when this deficit will begin to affect functional performance with either uninjured or previously injured people. Hurley *et al*., (1998) did find a moderate significant correlation between JPS acuity measured using a similar open chain sitting protocol to this thesis and functional time score, suggesting function declines with JPS ability decline. However, the time score was accumulated from "get up and go", timed walk, stair ascent and stair descent tasks, thus may not be seen a valid functional tests for younger and healthy participants. Further, Gokeler *et al*., (2012) completed the most recent review into proprioceptive ability and functional performance following an ACL injury. The review considered any paper with sufficient quality that correlated JPS and/or TTDPM measures to strength, gait, knee laxity, hop tests, balance and/or patient-reported outcome scores. None of the functional tests had strong correlations to either JPS or TTDPM, the majority of correlation scores were low to moderate at best. Furthermore, the overall mean effect size of the correlations was just 0.4 which again shows a small correlation strength. The authors interpret this result in two ways; the first being the patients included in the review paper did not have a proprioceptive deficit large enough to cause functional declines. Indeed ACL patients produced a mean average error score of just 0.8° - 0.5°. This is much lower than the ACL patients in the current thesis (7.2° - 8.1°). The second interpretation being measurement tools were not sufficiently tested for reliability and validity and hence studies had low methodological quality. As discussed previously in this section, measurement error may then mask true proprioceptive ability. Gokeler *et al*., (2012) call for new proprioceptive measurement tools be developed and used to compare to functional performance.

Other papers have further attempted to link proprioceptive ability to functional performance. Foch and Milner (2013) considered the relationship between both weight bearing and non-weight bearing knee and hip joint position sense to running performance (specifically peak stance knee and hip angles). Out of the four relationships considered, only one had a moderate correlation. In summary, it would appear there is no strong evidence to relate proprioceptive ability to functional performance.

However, there is significant evidence (see section 5.2.3) to suggest regular physical activity can have a positive impact on knee joint position sense. Perhaps specific proprioceptive rehabilitation or pre-habilitation programmes are not needed. It may be more affective to simply keep people physically active. Tsang and Hui-Chan (2004, 2003) reported significant correlations between knee joint position sense ability and limits of stability; thus elderly participants with better proprioceptive acuity had better dynamic balance. Dynamic balance is

a key factor in successful motor control. Therefore particularly in the elderly population there may be a more important link between knee JPS and function that is yet to be reported.

5.6 Limitations

This section will discuss the limitations of this thesis; divided into four sections. The first will discuss the effects of muscle history, known as thixotrophy, on knee joint position sense. The second will discuss the sense of effort or force on knee joint position sense. The third will discuss the current view of static proprioception measures. Lastly, the fourth section will discuss muscular strength.

Thixotrophy

One potential limitation of this thesis is the lack of acknowledgement of a well-known muscle characteristic called thixotrophy. Thixotrophy is described as the dependence of a muscle's passive properties on the previous contraction and length change history (Weiler and Awiszus, 2000, Gandevia, 2014). Thixotrophy properties are present in both intrafusal and extrafusal muscle fibres (Cordo *et al*., 2002). This characteristic can cause slackness or stiffness (depending on the direction of the prior movement) in the muscle due to previous contractions which results in a change in the resting discharge of the spindles; this specific reaction is known as length-dependent muscle conditioning (Proske, 2006). Further, if a muscle is conditioned in a flexed position prior to movement to a target angle in joint position sense measures the muscle will become stiffer and increase resting discharge rate (Proske, 2006, Gandevia 1014). However, the opposite occurs if the muscle is extended prior to positioning; the muscle becomes slacker and the resting discharge rate reduces (Proske, 2006). Thus, thixotrophy may negatively affect joint position sense (Gandevia, 2014); it has been suggested that an increase in 1° of error for every 2-3 imp.s^{-1} of resting discharge rate change (Gregory *et al*., 1988).

However, it is important to note that even the most current research into thixotrophy and joint position sense (Tsay *et al*., 2014) was studied on the elbow joint; there is no research to consider the lower limb or knee joint. Furthermore, the major effects of thixotrophy occur during passive positioning and passive repositioning protocols, when there is limited formation of cross-bridges due to the absences of active contraction (Proske, 2006). The knee JPS technique involved in the current thesis involved passive and active motion. Therefore, thixotrophy may be more important to consider in threshold to detect passive motion measurements, where the protocol only includes passive motion. Participants were given practice trials to become

familiar to the protocol and the direction of movement was randomised. Furthermore it is known thixotrophy effects reduce over time, hence the effect of thixotrophy may have been removed by the time data collection occurred (Tsay *et al*., 2014). This, this issue, although acknowledged, would not have significantly affected the results of the thesis.

Sense of effort

During experiments into the effects of thixotrophy on passive position sense, authors such as Proske (2006) and Gandevia *et al*., (2006) began to consider if there were any effects during active voluntary contraction and if not why not? One aspect of the answer is an area of proprioception that has been relatively ignored in research with comparison to position and displacement sense, the sense of effort. A sense of effort was first suggested by Ekbolm and Goldbarg in 1971 during work on the validity of the Borg scale or Rate of Perceived Exertion (RPE); it appeared participants had different senses of effort from different body parts and exercise types during similar intensity exercise. Early work presented evidence of this additional sense during joint proprioception testing; Gandevia *et al*., (1993) induced total body paralysis to participants, however they still reported a sense of ankle movement when asked to plantarflex this joint despite this being impossible. Later work by the same research group (Gandevia *et al*., 2006) blocked just the hand from all afferent and motor fibres using a pressure cuff and anaesthetic. Results indicated the participant could still sense the position and movement of the hand up to 20°. Both results were attributed to a sense of effort produced by the motor command itself (Gandevia *et al*., 2006). Future studies added that effort sense was available whenever afferent signals were present and even during isometric contractions (Smith *et al*., 2009). Thus during active, voluntary contractions the central nervous system generates an effort sensation alongside the motor command signal (Walsh *et al*., 2004). Therefore, the sense of position may well arise from both afferent peripheral proprioceptors but also from centrally driven signals (Semmler and Miles, 2006).

This additional sensation is thought to enhance positional sense; but may not be thought of as a proprioceptive signal in its own right (Proske, 2006). Moreover the sense of effort may be the outcome of a central calculation made using the efference copy; this being the difference between the re-afferent (all the afferent signals from generated by fusimotor impulses) and ex-afferent (response due to environmental stimulus) components of the total spindle system which equates to the conscious perception of the movement (Winter, 2005). Therefore the

sense of effort may contribute optimally at normal voluntary contractions without additional load, but with cues taken from the effects of gravity.

The role of gravity in joint position sense has been considered (Proske, 2005). In environments with micro-gravity or macro-gravity the sense of effort is altered and thus active proprioception ability declines (McIntyre *et al*., 1998, Young *et al*., 1993, Harris *et al*., 2014). For example in a 2g environment participants found completing an ascending stepping task required "*unusually great effort*" (Matthews, 1988, p.437). The proprioceptive ability is further hampered in the absence of both gravity and vision (Young *et al*., 1993). Also, when torque about the limb is manipulated, position sense declines (Worringham and Stelmach, 1985). Furthermore, it is important to report the findings of position sense measures in the horizontal plane and hence gravity-neutral positions; the elbow for example has reduced position sense errors and hence increased static proprioception ability in the horizontal compared to the vertical plane (Walsh *et al*., 2006). This may explained by the absence of additional cues from gravity, and a potential reduction in the contribution of the sense of effort.

Studies investigating the effect of fatigue, muscle conditioning and vibration on joint position sense contribute to our understanding of the sense of effort. For example studies have reported that when the sense of effort is removed by supporting the limb, position error increases (Winter *et al*., 2005, McCloskey, 1973, Horch *et al*., 1975, Gregory *et al*., 1988). Indeed Goodwin *et al*., (1972) over 40 years ago reported position errors of between 12-15 degrees if the limb was held by the researcher. Evidence also shows that the decrease in matching error when the limb is not supported is not due to an increase in muscle spindles activity, as an increase in load on the limb does not reduce the error further (Winter *et al*., 2005).

In addition, the sense of effort may be more resilient to fatigue than position sense as it is driven by the central nervous system and not the peripheral components (Hunter *et al*., 2004). This may provide another explanation for the results of study 4.4 in which peripheral / muscular fatigue did not reduce joint position sense; the protocol did not have any negative effect on the sense of effort. Therefore, following the fatiguing protocol there may have even been an increase in the sense of effort contribution (as the CNS contribution increases) and therefore this compensated for any potential losses of peripheral damage and hence position sense. Indeed previous research has found fatigue can increase the sense of effort (Proske, 2005, Enoka and Stuart, 1992) which may improve position sense. Fatigue is now seen as a centrally driven state or even an emotion or sensation (Noakes, 2012). Thus, it is clear the effects of

fatigue on joint position sense must consider the central components in addition to the peripheral affects (Ament and Verkerke, 2009, Noakes, 2012).

In summary, the sense of effort may provide the "…*absolutely essential service of informing the CNS of the over-all state of the muscular system and the ability of muscle to provide desired contractions*" (Cafarelli, 1982, p.388). Therefore it is becoming increasingly evident a component of joint position sense may be derived from the motor command that generates the movement (Proske, 2006, McCloskey, 1978). Ultimately, this sense may be essential to the homeostasis of muscular performance and is hence another aspect of the body's survival mechanisms (Cafarelli, 1982). Swart *et al.*, (2012) recently proposed a task effort and awareness scale (TEA) to begin the measurement of this sense. Thus, future work may consider measurement of both position sense and the sense of effort to give a more optimal idea of proprioceptive ability.

As an additional note, readers should not confuse the sense of effort with the sense of force; they are separate entities (Enoka and Stuart, 1992, Brockett *et al.*, 1997). It is thought the sense of force is a combination of the sense of effort and the force production output (Jones, 1986). A good example of this is to consider the relationship between perceived effort and force; it is clear perceptions of force are apparent at much lower thresholds that perception of effort (Enoka and Stuart, 1992). Furthermore, it is suggested the sense of force is peripherally driven, whereas the sense of effort is centrally driven (Brockett *et al.*, 1997, Ament and Verkerke, 2009). Sense of force can be measured using matching force tasks based on the individual's maximum voluntary contraction. Future studies might also consider this measurement.

Proprioceptive measurement

Knee joint position sense and threshold to detect passive motion are the two most common measures of knee proprioceptive ability; however this does not mean they are the most optimal techniques for illustrating proprioceptive ability. In this thesis a sitting, open kinetic chain, protocol was used for JPS data collection. The benefits of this technique are three-fold; 1.) All populations are able to complete the testing due to minimal joint loading therefore large scale normative data collection is possible; 2.) The knee joint can be isolated, so practitioners can be more confident they are measuring static knee proprioception without input from adjacent joints; 3.) The testing requires minimal participant training prior to data collection hence it is relatively quick and easy to complete. However, there are potential limitations to using passive-active, open-chain JPS protocols. It has been suggested that active-active, closed-chain

protocols are more ecologically valid for collecting JPS ability as the movements and joint loads are more similar to everyday movement (Herrington, 2005, Ghiasi and Akbari, 2007, Stillman and McMeeken, 2001). Although, interestingly, current research has failed to provide strong evidence to support a relationship between joint position sense data (from any protocol) and functional activity (Marks *et al*., 1993, Bennell *et al*., 2003, Lee *et al*., 2009). For example Lee *et al*., (2009), Marks *et al*., (1993) and Bennell *et al*., (2003) did not find a significantly correlation between knee joint position sense and functional lower limb tests. Roberts *et al*., (2007) did find a relationship between a joint position sense index and single leg hop distance in ACL deficient patients, however, the calculation of an index of static proprioception is not a common variable and hence we cannot be certain this finding would hold true using other more popular measurements. To summarise, a sitting protocol similar to the one used in this thesis may have limitations to ecological validity. But further research is needed to provide evidence of a link between clinical JPS measurement and functional movements, and then ecological validity can be confirmed or rejected.

In addition to the issue of ecological validity, the measurement error and hence practical usefulness of the reported JPS protocol should be briefly discussed here (see section 5.5 for a more detailed analysis). Smallest detectable differences were reported to be up to 67% of the absolute error score, this has obvious limitations. Further, the effect sizes of the normative correlation data were small to moderate. Therefore, JPS measurement may have practical limitations if taken from an uninjured population, for example when screening a sports team. However, effect sizes were large when considering the ACL patient groups; hence it may be more relevant to use JPS measurement with these populations. Further research needs to consider larger ACL patient groups and other injured populations to develop our understanding of joint position sense and injury.

It is also evident that other protocols have been developed. For example Al-Othman *et al*., (1998) presented a weight-bearing knee raise test that focussed on accuracy in returning the foot to the same position on ground contact. This attempt to involve one complete movement from initiation, to a target position, back to the starting position may represent the more cyclical motions of human movement, therefore a more functional and ecologically valid test of proprioception positioning. However, no reliability or validity of this novel measurement analysis was reported. It may also be more appropriate to collect knee joint-position-sense using an active-active method, as it is again more ecologically valid (Lin *et al*., 2006, Kalaska, 1994). Han *et al*., (2014) stated tasks in sensory measurement should be stimulus-response

compatible (i.e. as natural a movement as possible). The active-active protocol in this thesis had poor reliability and could not be implemented in the additional studies. Future studies should aim to develop this protocol, perhaps incorporating a more individualised set-up and a familiarisation session to improve reliability scores.

The majority of knee joint position sense is collected in the sagittal plane. However ACL injury occurs as a combination of movements in sagittal, frontal and longitudinal planes. Therefore, more recently Mir *et al*., (2014) considered knee position sense in knee valgus and varus positions, thus in positions more similar to that during ACL injury. Reliability was reported as an ICC of 0.74 in the ACL risk position, which is moderately high. Also, position error was significantly higher in an at-risk position than a normal position. Therefore researchers may wish to incorporate JPS in this plane in the future. Further, it is importantly noted that joint proprioceptive ability may differ from joint to joint (Matthews, 1987, Horch *et al*., 1975, Proske, 2006). For example it has been suggested that kinaesthesia ability is higher in proximal compared to that of distal joints (Proske, 2006). Practitioners should not generalise the methods used in the thesis to other joints.

The validity of any measurement relies on our knowledge of the systems that control that measure. Figure two attempted to illustrate the required knowledge to design valid joint position sense measures. It has been suggested if proprioception was a simple afferent – efferent or input – output system errors in motor control would be much greater (see Burgess *et al*., 1982, McCloskey and Torda, 1975, Kalaska, 1994). Indeed it is well known motor performance decreases if efferent (McCloskey and Torda, 1975) or afferent (Marsden *et al*., 1984, Mott and Sherrington, 1895) is provided in isolation. As such Ashton-Miller *et al*., (2001) presents a model in figure 21 that appreciates the roles of both afferent and efferent information and builds on the detail of these processes.
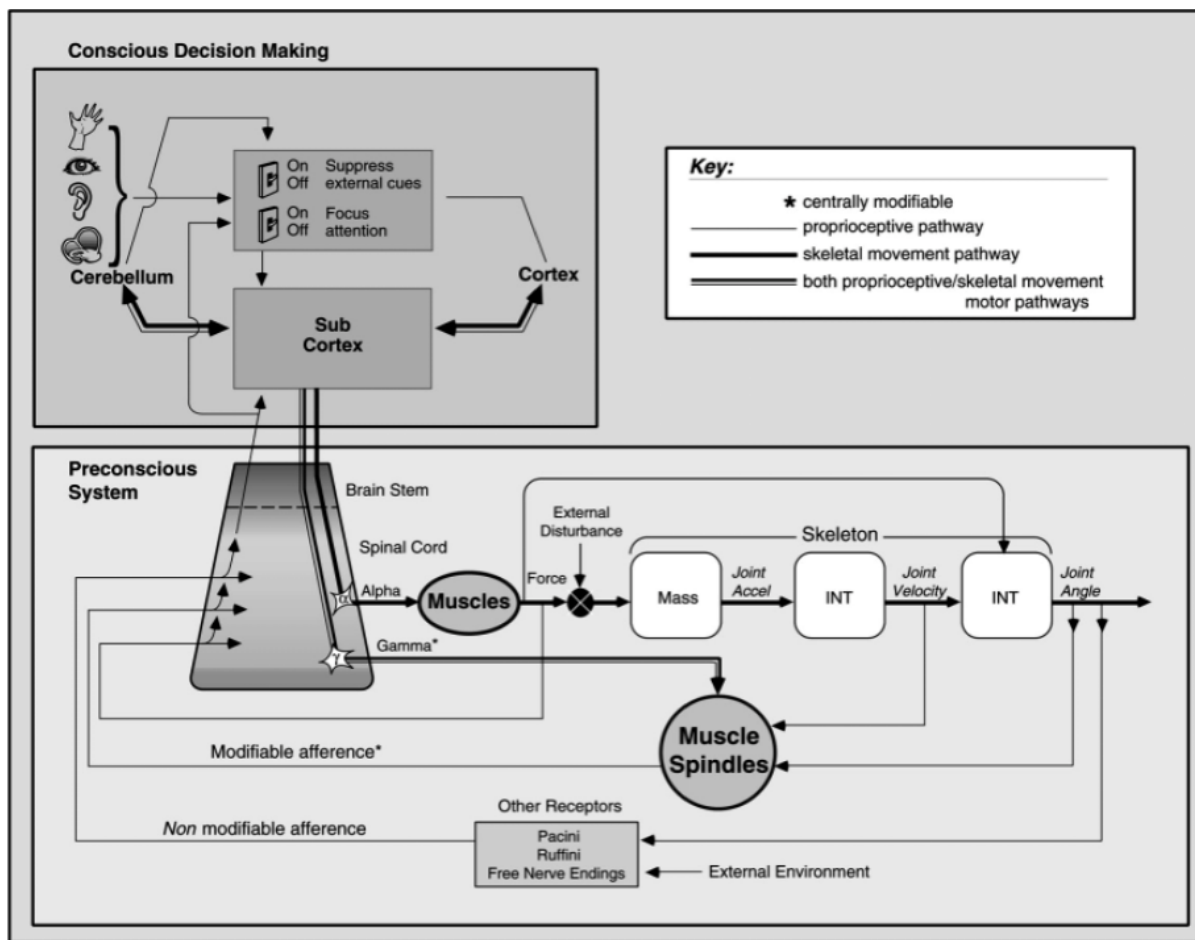
Figure 21. Taken from Ashton-Miller *et al*., (2001) p.130. A more detailed scheme of the pathways and functions of proprioception. INT indicates mathematically integration. See text for more detail.

The lower box in figure 21 explains the autonomous aspect of proprioception below the brain stem. This is similar to the lower sections of figure two, however provides more detailed information on the hierarchical role of the mechanoreceptors. The muscle spindles are centrally modifiable and hence may have a more prominent role in afferent and efferent processing. Efferent signals via the alpha motor neurone pathway are integrated into joint positional information using segment mass, joint acceleration and joint velocity from the skeleton. The force and mass aspect of this diagram incorporates the sense of force discussed earlier. This detail is not appreciated in figure two.

The upper box details the conscious higher nervous system components of proprioception. The novel detail in this Ashton-Miller *et* al., (2001) figure is the complex appreciation and integration of attention and motivation in proprioception, which contribute to the sense of effort. Attention may be critical to proprioceptive ability as this may be the neuropsychological process that decides which afferent information is relevant (Ashton-Miller *et al*., 2001,

Kalaska, 1994). There has been extensive research in the area of attention and motor tasks, however not much of this literature considers proprioceptive ability (Han *et al*., 2014). This is evident when patients are being rehabilitated following knee injury; they have to pay more attention to body movements to be successful. Figure 21 also highlights the significant role of the cerebellum, particularly in feed-forward processes; to combine and control all sensory inputs. The cerebellum may control muscle stiffness around the knee joint, in preparation for impending loads (Ashton-Miller *et al*., 2001). Schmidt (1971) critically identified the need for anticipatory responses in motor control, which may be the cerebellums important role in proprioceptive processing. This is supported in commentary from Boisgontier and Swinnen (2014) who support the notion that active movement to a target angle in joint position sense is improved because of feed-forward predictive models provided by the cerebro-cerebellar loop. Therefore, clinical practitioners should include active movement when measuring joint position sense to ensure the cerebellum is included in processing as would be during normal activity.

The additional elements to the proprioceptive processes have yet to be confirmed by extensive primary research. However, in future studies it may be necessary to attempt to appreciate and even measure the possible contributions of attention, motivation and feedforward/ predictive modelling to understand an optimal proprioceptive state. Therefore, in comparison to figure two it is apparent proprioception may have been overly simplified in previous understandings and hence the measurement of knee joint position sense may need to be re-designed to take into consideration the various higher processing factors not appreciated in previous studies.

Rehabilitation and pre-habilitation programmes may therefore improve both peripheral and central processes of proprioception; 1.) Increases in the fusimotor drive to spindles in challenging tasks 2.) Increases in the gain of the spinocerebellar and dorsal column-medial lemniscal pathways receiving afferent information 3.) Improve attention to relevant afferent - information. (Ashton-Miller *et al*., 2001).

The Ashton-Miller *et al*., (2001) model clearly attempts to incorporate a more detailed picture of proprioception. However back in 1988 Matthews identified key problems with modelling and measuring what he called "complex messages" from proprioceptors and the accompanying "complex processing" of afferent information. Thus, future proprioceptive measurements may be limited die to these problems. The first issue is the complexity of proprioceptor firing rate; this is based on the relationship between length and contraction type and can also be affected

by both primary and secondary receptor inputs. Thus, no one receptor gives one clear linear variable but rather a range of information based on many variables (Gandevia, 2014). The second problem again regards firing rates, but specifically when the limb is static. The afferent information from the involved limb in this condition is not only based on the current position, but the direction in which the limb travelled to this position (shortening or lengthening of muscles) and the length of time in this position; the path to the target position contributes to static appreciation of position sense (Horch *et al.*, 1975). In the thesis this was only appreciated by keeping the angular velocity during passive placement of the knee constant and the target angle within a 30° area. Thirdly, joint position sense measurement techniques must appreciate afferent information comes from both agonist and antagonist muscle groups; hence theoretically any injury effect on JPS may be masked/ compensated by the opposing muscle group. Further, the distribution and density of spindles within and between muscles is not uniform (Gandevia, 2014). Making things even more complex is the evidence to suggest spindle density is not correlated to proprioceptive performance (Gandevia and Burke 1992a). Finally, the classification of joints may also impact JPS ability; what may appear a simple hinge joint with one degree of freedom may indeed have muscles crossing more than this joint that contribute to multiple position senses.

Figure 21 does go some way in addressing Matthews' (1988) issues. The complexity of proprioceptor firing rates, specifically the muscle spindles, with the appreciation of the skeletal contributions to position sense and also external perturbations in the lower section of the model. However, the model does not identify the differences between joint position sense and kinaesthesia that has been suggested (McCloskey, 1978). Furthermore, all proprioception tests are global –as yet they cannot directly measure a specific ligament (such as the ACL) proprioception ability (Pincivero *et al.*, 2001, Gokeler *et al.*, 2012).

Recently Gandevia (2014) and Boisgontier and Swinnen (2014) commented proprioception is still poorly understood and we have made little progress on Sherrington's work in 1906. Gandevia (2014) proposes this is due to the multi-disciplinary nature of proprioceptive research; this includes areas of physiology, neurology, structural biology, anatomy, rehabilitation, motor control to name but a few. Furthermore, Gandevia states this cross-discipline but separate research has for too long "…*overemphasized the apparently separate perceptual (and other) effects due to activity in one anatomical class of receptor…rather than those orchestrated effects that their usual combination evokes*" (2014, p.200).

This may be the reason why proprioceptive measurement in the clinical setting appears to have ignored much of the central processes; it may be too complex to measure (Matthews, 1988, Gandevia, 1992, Boisgontier and Swinnen, 2014). It is still very difficult to measure proprioception, not least because we are largely unaware of the signals generated by our own movement (Proske and Gandevia, 2009) and yet we ask subjects to become conscious of our proprioception when testing our ability. Furthermore, during movement and only during movement, action-related signals are copied, stored and made accessible however erased when movement ceases (Proske, 2006). Both issues present significant challenges to the measurement of joint position sense. To date the majority of joint position sense measures eliminate any visual and vestibular input. However, including this information in addition to mechanoreceptor afferents may provide the optimal proprioceptive performance (van Beers *et al*., 1999). Therefore future studies may incorporate this into their measurements of joint position sense to see if ability does indeed improve.

This thesis has identified the most reliable, valid and sensitive method for knee joint position sense. However, knee joint position sense is currently one of the most popular methods of knee joint proprioception but not necessarily the best. We may not have developed the "best" test for proprioception, which may need to incorporate more appreciation of the central processes of proprioception and until then we may not be able to assess the full extreme of clinical and functional significance of proprioception.

Muscular Strength

Another potential limitation of this thesis is the lack of inclusion of muscular strength measurements. Since joint proprioception is in part reliant on muscle spindle input, it may be intuitive to believe there is a relationship between muscle strength and proprioceptive ability. There is certainly much literature on the effects of age on muscular strength. For example, in early work Vandervoort (1992) and Stalberg *et al*., (1989) demonstrated a decline of up to 45% in muscular knee strength in older adults (greater than 70 years). There is also much evidence to support the total number of motor units reduces with age (for example; Faulkner *et al*., 2007, Doherty *et al*., 1993). However, there is very limited evidence to link a reduction in motor unit function, from either age, injury or fatigue, to a reduction in proprioceptive ability. Indeed, Segal *et al*., (2010), Espanha *et al*., (2012) and van der Esch *et al*., (2007) could not find any significant relationships between lower limb strength and knee JPS ability in OA patients. Lund and Juul-Kristensen (2010) also considered OA patients and could not find a relationship

between knee proprioception and knee strength. However, some weak correlations were found between muscle strength in the triceps brachii and dynamic proprioception over the elbow joint. Although, no clear explanation is provided for this result in knee OA patients. Further, there may be a weak relationship between abdominal strength and trunk position sense, but this correlation was only highlighted in chronic lower back pain patients, not healthy controls (Yılmaz *et al.*, 2010). Levinger *et al.*, (2012) found improvements in lower limb strength following knee replacement surgery but not knee proprioception, again suggesting the two variables are not directly related and one can improve without impacting on the other. So, it appears there is very little evidence to support a link between knee proprioceptive acuity and muscular strength performance.

This may be explained with consideration of the proprioceptive process; although joint proprioception process does involve integration of muscle spindle action, it is not wholey reliant on muscular contraction as a stimulus. Contributions from

As results of study 4.4 confirm, muscular fatigue does not appear to reduce proprioceptive ability. Again, this may be due to the additional components of proprioception; including central processing, sense of effort and joint mechanoreceptors, compensating for muscle unit function decline. Hence, this explains the lack of evidence for a muscular strength and proprioception relationship. Future research might consider muscular strength, proprioception and their relationship to function.

Chapter 6 Conclusion

6.0 Conclusion

The overall aim of this thesis can be divided into two sub-sections. The first aim involved measurement; to find the most optimal condition from three most popular protocols to record knee joint position sense ability. The second aim involved implementation of this tool; to report the effects of various independent variables on knee joint position sense ability. The different components of each aim will be concluded individually in the section below.

The reliability and validity of knee joint position sense measurement techniques was reported in the first section of the thesis. The most reliable, in terms of test-retest, inter-rater and intra-rater reliability, JPS method was identified as follows; a sitting position, either leg, knee flexion through 60°-90° from a starting position of 0° and knee extension through 30°-60° from a starting angle of 90°. Five trials were adequate for consistent results and absolute error scores were more reliable than relative error scores. The results of a construct validity analysis revealed the use of an IKD may not be necessary, clinical environments using image capture provided statistically similar (knee flexion) or increased (knee extension) joint position sense ability. Between practitioner validity was also confirmed, therefore multiple practitioners can analyse JPS images if required. Clinicians may adopt this method when measuring knee joint position sense.

A large scale (N= 116) study based on the UK population provided normative knee joint position sense measures across five age groups. The values of knee JPS into flexion were 3.6°, 3.9°, 3.5°, 3,7° and 3.1° for ages 15-29, 30-44, 45-59, 60-74 and 75+ years old respectively. The normative values for knee JPS into extension were 2.7°, 2.5°, 2.9°, 3.4° and 3.9° for ages 15-29, 30-44, 45-59, 60-74 and 75+ years old respectively. Clinicians or sports therapists may use these normative values when screening uninjured patients or athletes for any increased risk of injury, for example if the patient is more than two standard deviations above the normative value or has an absolute error score above 5° this may be a cause for concern. The direction of movement did affect error scores and hence both flexion and extension should be used in any knee JPS measurements. There were also some significant correlations between knee joint position sense and age, BMI, activity levels and knee condition. Specifically, as age and BMI increased, JPS into extension worsened and as activity level and knee condition increased, JPS into extension improved. Therefore clinicians should acknowledge that each of these variables may be related to the knee joint position sense ability of the patient. However, as these relationships were mild to moderate, application of these findings should be done with caution.

A non-athletic ACL deficient population had poorer joint position sense ability compared to their contralateral leg and an external control measured using the recommended knee joint position sense method. The ACL patients had a knee JPS error score of 7.9° compared to the contralateral knee score of 2° and external control group score of 2.6°. ACL injury and then reconstruction also significantly reduced the knee position sense ability of an elite athletic population when compared to the uninjured knee and external controls. The injured knee produced knee error scores of 8.1° and 7.2°, the uninjured knee produced 3.5° and 1.9° of error and the external controls produced 3.1° and 2.8° of error into knee flexion and extension respectively. This may be due to the loss of functional mechanoreceptors in the knee joint following ACL damage The results of an initial cluster analysis of patients included knee injuries other than ligament damage did not have reduced joint position sense ability. Therefore, clinical practitioners should pay particularly attention to improving proprioception when treating patients with ACL injury.

The final study in this thesis considered the effects of peripheral / muscular fatigue on knee joint position sense. The results suggested peripheral/ muscular fatigue alone may not reduce joint position sense of the knee. A peripheral fatiguing protocol may not be successful in fatiguing and hence debilitating all components of static proprioception. Other types of mechanoreceptors situated in the joint, skin and tendons may compensate for the loss of effective muscle receptors during fatigue. Furthermore, evidence suggests it is very difficult to fatigue intrafusal muscle fibres and hence these may well continue to provide afferent information as extrafusal muscle fibres are fatigued. Importantly, peripheral/ muscular fatigue measured using torque output does not indicate a reduced function in the central mechanisms of proprioception. Thus the spinal cord, brain stem, cerebral cortex and cerebellum may compensate for the fatigue in muscle spindles around the knee joint by increasing task attention, motor neurone activity and the sense of effort. This is not to say fatigue does not affect static proprioception, rather clinical practitioners and researchers should consider central fatiguing protocols and knee joint position sense in the future.

The clinical application of the results in this thesis is that patients with ACL injury are likely to have reduced knee joint position sense ability. However, it is noteworthy that high smallest detectable difference values were reported in the reliability analysis and therefore clinical practitioners should acknowledge this when recording knee JPS progression. Furthermore, researchers need to address the suitability of proprioceptive exercises in rehabilitation and evaluate their effects using reliable and valid measurement techniques. There is also need for

studies into the functional relevance of knee joint position sense, as yet there is limited evidence that proprioception is related to functional performance.

The reliability and validity of knee joint position sense in the frontal and axial planes is required along with joint position sense studies in other joints. The development of an active-active protocol that is appropriate for all ages should also be considered. In addition researchers should consider including a measurement of the sense of effort and/ or sense of force in studies. There is also a need to approach proprioceptive research from an inter-disciplinary viewpoint. This will enable a better understanding of the central processes involved in proprioception including task attention, motivation and anticipation. Ultimately we may then be able to discover if and how proprioceptive ability can be modified.

Appendices

Appendix 1: Published Studies

Appendix 1a: Relph, N., Herrington, L., and Tyson, S. (2014). The effects of ACL injury on knee proprioception: A meta-analysis. *Physiotherapy*, 100 (3), 187-195.

Appendix 1b: The scoring system used in the meta-analysis.

Appendix 1c: The characteristics of studies excluded from the meta-analysis

Appendix 1d: Relph, N., & Herrington, L. (2015). Inter-examiner, intra-examiner and test-retest reliability of clinical knee joint position sense measurements using an image capture technique. *Journal of Sport Rehabilitation* (in press).

Appendix 1e: Relph, N., & Herrington, L. (2015). Criterion-related validity of knee joint position sense measurement using image capture and isokinetic dynamometry. *Journal of Sport Rehabilitation*, Technical Report 10 (http://dx.doi.org/10.1123/jsr.2013-0119).

Appendix 1f: Relph, N., & Herrington, L. (2015). The Effect of Peripheral Fatigue on Knee Joint Position Sense. Paper presented at the *International Society of Biomechanics Conference*, Glasgow, UK

Appendix 2: Participant Information Sheet for Clinical JPS Testing

Appendix 3: Participant Informed Consent Form for Clinical JPS Testing

Appendix 4: Isokinetic Dynamometer Protocol

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Appendix 1a: The Effects of ACL Injury on Knee Proprioception: A Meta-Analysis

Physiotherapy

Systematic review

The effects of ACL injury on knee proprioception: a meta-analysis

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Abstract

Background It is suggested the anterior cruciate ligament (ACL) plays a significant role in knee proprioception, however, the effect of ACL injury on knee proprioception is unclear. Studies utilising the two most common measurement techniques, joint position sense and threshold to detect passive motion, have provided evidence both for and against a proprioceptive deficient following ACL injury.

Objective The objective of the study was to undertake a meta-analysis investigating the effects of ACL injury, treated conservatively or by reconstruction, on proprioception of the knee, measured using joint position sense and/or threshold to detect passive movement techniques.

Data sources Seven databases were searched from their inception to September 2013 using the subject headings 'anterior cruciate ligament, proprioception, postural sway, joint position sense, balance, equilibrium or posture' to identify relevant studies.

Eligibility criteria PRISMA guidelines were followed as much as possible. Studies that investigated the effect of ACL injury on either knee joint kinaesthesia or position sense were included in this review.

Data extraction and synthesis Two reviewers independently extracted data using a standardised assessment form. Comparisons were made using a fixed effect model with an inverse variance method using Review Manager Software (V5.1).

Results Patients with ACL injury have poorer proprioception than people without such injuries ($SMD = 0.35°$; $P = 0.001$ and $SMD = 0.38°$; $P = 0.03$) when measured using joint position sense and threshold to detect passive motion techniques respectively. Patients had poorer proprioception in the injured than uninjured leg ($SMD = 0.52°$; $P < 0.001$) and the proprioception of people whose ACL was repaired was better than those whose ligament was left unrepaired ($SMD = -0.62°$; $P < 0.001$).

Limitations Heterogeneity of measurement techniques and lack of psychometric details.

Conclusion ACL injuries may cause knee proprioception deficits compared to uninjured knees and control groups. Although differences were statistically significant, the clinical significance of findings can be questioned. Clinical practitioners using joint position sense or threshold to detect passive motion techniques need to consider the reliability and validity of data provided.
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Keywords: Anterior cruciate ligament (ACL); Knee proprioception; Joint position sense; Threshold to detect passive motion

Introduction

The anterior cruciate ligament (ACL) controls knee movement in six directions; three rotations and three translations and thus is critical for stable lower extremity movement [1]. The ligament's main role in knee joint stability is to prevent excessive anterior translation (forward movement) of the tibia in relation to the femur and help direct the 'screw-home' mechanism which occurs during femoral and tibial rotation into full knee extension [2]. The ACL is also thought to play a significant role in knee proprioception [2]. Proprioception is a component of the somatosensory system which plays an important role in normal human performance [2–4]. Its main aim is to provide afferent information on the position and movements of a joint. In the ACL, 1% of its total area [5] is made up of three types of proprioceptive receptors; pacinian capsules, ruffini nerve endings and Golgi tendon organs [6], each has a specific role. The pacinian capsules adapt rapidly to low degrees of joint stress, are sensitive to rapid changes in accelerations and classified as dynamic receptors [7]. Whereas, ruffini nerve endings and Golgi

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tendon organs are slow adapting with a high threshold to stress and are believed to provide information on the position of the knee joint [7].

Following ACL injury, secondary problems such as osteoarthritis are common [8,9]. It has long been thought that ACL injuries can be detrimental to proprioception of the knee and this may lead to abnormal movement patterns which are a mechanism for further injuries and long-term secondary problems [9]. However, research in to the effects of ACL injury on knee proprioception has yielded conflicting results [10]. Therefore, we undertook a systematic review with meta-analysis of pooled data to investigate the effects of ACL injury, whether treated conservatively or by reconstruction, on proprioception of the knee. The two most common proprioception measurement techniques [11]; joint kinaesthesia (threshold to detect passive motion) and joint position sense were considered. Joint position sense (JPS) involves passively moving a joint to a target angle, then the patient actively reproduces this angle [11]. Joint kinaesthesia traditionally measures the passive movement of a joint before movement is detected, called a threshold to detect passive motion (TTDPM). This involves asking the patient to indicate the first instance they perceive motion of the joint [11].

Methods

Protocol

No review protocol exists for meta-analysis of descriptive data, thus the PRISMA guidelines on meta-analysis were followed as far as was practicable for the type of data concerned (http://www.prisma-statement.org/statement.htm).

Data sources

The following electronic databases were accessed from their inception to September 2013: AMED, CINAHL, PubMed, Medline, PeDro, Sports Discus and the Cochrane Library. Primary journals in the field: *The Knee, American Journal of Sports Medicine* and the *British Journal of Sports Medicine* were also manually searched, as were the reference lists of all selected studies to ensure the search was comprehensive. Key terms were: anterior cruciate ligament, proprioception, postural sway, joint position sense, balance, equilibrium or posture using the Boolean operator 'OR'. Limits of the search were: English language studies (none of the researchers spoke foreign languages); human studies, adult participants and peer reviewed published full access articles. Unpublished literature and trial registries of current studies were not included in the search.

Study selection

Studies were eligible for inclusion if they (1) investigated proprioception of the knee following ACL injury

(conservatively managed or reconstructed) (2) recruited adults (over 16 years) with an ACL injury, including participants with ACL injuries combined with meniscus and/or collateral ligament damage and (3) included a primary outcome measure of knee proprioception measured by mean angle of error in degrees. The primary outcome measure could take two forms; studies measuring knee kinaesthesia used the TTDPM method where the mean angle of error was defined as *the difference in degrees from initiation of motion and the participant's perception of motion*, studies measuring JPS utilising an index angle matching method in which the mean angle of error was defined *as the difference in degrees between the target angle and the angle reproduced by the participant*. The type of control measure (the participant's contra-lateral leg or the leg of an external matched control) was also collected along with the corresponding data.

Study selection

The search results were merged using reference management software (Endnote X6) and duplicates removed. The titles and abstracts were screened and articles which obviously did not meet the selection criteria removed. The full text of the remaining studies was then checked against the selection criteria. Studies with outcome data that did not meet our criteria were excluded at this stage. The selection of appropriate articles was agreed through discussion between two authors (NR and LH) and a third party was available to arbitrate if necessary.

Quality assessment

The methodological quality of the studies that met the selection criteria was appraised by two of the research team independently to identify studies that had a low risk of bias. There is no established tool to assess the methodological quality of descriptive studies, therefore we amended a quality assessment tool previously developed and used by the authors [12]. This tool considered eight potential sources of bias; confirmation of ACL deficiency, representation of population, representation of sample, homogeneity of participants, sample size, study design, assessor blinding/bias, statistical analysis (available from NR). Summating the scores for items on the assessment gave a maximum score of 88. The methodological quality scores were arbitrarily, but logically, grouped as 'poor' (a score of less than 29/88), 'moderate' (a score of 30 to 58/88) or 'good' (a score of 59+/88). Studies of moderate to good quality (that is, 30 to 88/88) were selected as providing data of sufficient low risk of bias to enter in to the meta-analysis.

Data extraction and analysis

Studies that met the eligibility criteria and were of sufficient quality were included in the meta-analysis. The following data were extracted by one reviewer: the number

of participants, mean angle of error measured using TTDPM and/or JPS methods and accompanying standard deviation values to include in the meta-analysis and the following comparisons were made.

For joint position sense data:

- ACL injured leg vs contra-lateral leg control.
- ACL injured leg vs external control leg.
- Patients with a reconstructed ACL vs patients with a deficient ACL.

For data on the threshold to detect passive motion:

- ACL injured leg vs contra-lateral leg control.
- ACL injured leg vs external control leg.

The comparisons were made using a fixed effect model with an inverse variance method and presented as forest plots using Review Manager Software (version 5.1). Standard mean difference between groups measured the effect size. Heterogeneity between comparable trials was tested using the Chi-squared test (level of significance $= P < 0.10$ [13]). Heterogeneity was further tested using I^2 percentages to consider the impact potential heterogeneity would have on the meta-analysis.

Results

Study selection

The initial search strategy yielded 3076 articles, 2737 of which did not relate to the research question. Screening of the titles and abstracts of the remaining 339 articles revealed that 290 did not fully meet the inclusion criteria; the main exclusion factor was the use of techniques to measure proprioception other than TTDPM and/or JPS. A further 43 articles were excluded as they provided 'poor' quality data with a high risk of bias and/or had missing or inadequate outcome data. The main reasons for missing data were that median data were presented instead of mean data [14–16] or measures of the variability of the data (standard deviation) were missing [17]. This left six studies which were selected for inclusion in the meta-analysis. The flow chart detailing the selection process is shown in Fig. S1.

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.physio.2013.11.002.

Study characteristics

Six studies involving 191 ACL injured patients were selected (Table 1). Sixty-one participants were ACL deficient and 130 had had an ACL reconstruction. There were 82 healthy controls from five studies [18–22]. The participants' contralateral leg was used as the control in four studies [19,20,22,23]. Confirmation of ACL injury was provided by arthroscopy or MRI in five studies [18–22]. Only Barrack

et al. [18] stated a Lachman's test and Pivot Shift test had been used in addition to the arthroscopy. Mir *et al.* [22] did not report how the ACL injury had been confirmed. An autograft using the patella tendon was the most common surgery used to reconstruct the ACL [19–21] but, none of the included studies assessed laxity before and after surgery. Angoules *et al.* [23] was the only study to use the same surgeon for every reconstruction to minimise surgical skill as a confounder. Mir *et al.* [22] and Anguoles *et al.* [23] stated the type and number of surgical complications. None of the patients in the included studies had a previous ACL injury to the injured knee. One [20] stated patients with an ACL injury had concurrent damage to other structures in the knee during the ACL injury. A rehabilitation programme had been completed by patients in four studies [18,20,22,23].

All six selected studies were of moderate quality (Table 2). Most recruited a convenience sample [18,20,21,23]. Five studies matched the injured patients to controls by age [18–22] and four matched by gender [19–22]. None justified the sample size with a power calculation or the minimal detectable difference of the measurement tool. Two studies [18,23] blinded assessors to the type of participant.

Generally the statistical analysis in the selected studies did not provide appropriate detail (Table 2). For example, only two [22,23] reported whether the data was normally distributed and hence justified the use of parametric statistics. Most used 'home-made' measurement devices prepared specifically for the study but the reliability and sensitivity were infrequently reported. Indeed only two studies reported reliability statistics. Mir *et al.* [22] stated test–retest reliability using a correlation coefficient (0.99); however this was from a 'previous study' which was not referenced. Only one study [23] comprehensively reported the accuracy of their data collection methods, reporting the standard error of measurement (SEM), coefficient of variation (CV), smallest detectable differences (SDD) and intraclass correlation coefficients (ICCs) for each of their seven measures of knee proprioception.

During analysis, data from the external control subjects and patients with an ACL injury in some studies were used in several comparisons, for example if a control group was compared to patients with an ACL deficiency and a separate group of patients with an ACL reconstruction or if the same patients with an ACL injury were measured from two different starting positions [19,22]. Unfortunately the RevMan software did not allow us to stipulate the actual control and patient number values. However this number is clearly noted as a footnote to the affected figures and should be considered when analysing the comparison data.

Synthesis of results

Effects of ACL injury on JPS

Five studies compared the injured leg to the participant's un-injured leg ($n = 170$) as the control [19–23]. The pooled standard mean difference of mean angle of error was 0.52° (95% CI: 0.41 to 0.63; $P < 0.001$; $I^2 = 63\%$) indicating that the

Table 1
Characteristics of the articles included in the meta-analysis investigating the effects of ACL injuries on proprioception deficits.

Study	Participants	Age, mean (SD) and gender of patients with an ACL injury	Age, mean (SD) and gender controls	Equipment	Knee ROM	Method of measuring proprioception
Barrack et al. 2003 [17]	11 ACL-D 10 Controls	25 (NP) years 9 men, 2 women	25 (NP) years NP	Purpose built proprioception device	From a starting angle of 40° at an angular velocity of 0.5°/second	TTDPM – Mean angle of error in degrees from 10 trials randomly assigned to flexion or extension
Fischer-Rasmussen and Jensen 1989 [18]	20 ACL-D 18 ACL-R 20 Controls	ACL-D 27 (5) years 11 men, 9 women ACL-R 27 (5) years 9 men, 9 women	27 (4) years 11 men, 9 women (plus uninjured knees of patients)	Purpose built proprioception device	From a starting angle of 25° flexion to 15°, 20°, 25°, 30°, 35° or 60° flexion to full extension	JPS (passive positioning then active repositioning task) – mean angle of error in degrees from 20 trials randomly assigned to target angles
Fremerey et al. 2000 [19]	10 ACL-D 20 ACL-R 20 Controls	ACL-D 22.7 (3.2) years 7 men, 3 women ACL-R 28.4 (4.4) years 13 men, 7 women	26.4 (4.8) years 13 men, 7 women (plus uninjured knees of patients)	Purpose built proprioception device	From a starting angle of 0° to random target angles in 3 intervals; extension 0° to 20°, mid range 40 to 60° and flexion 80° to 100°. All passive motion was set at 0.5°/second	JPS (passive positioning then passive repositioning task) – mean angle of error in degrees from trials randomly assigned from the extension range, mid-range and flexion range
Ozenci et al. 2000 [20]	20 ACL-R (auto-graft) 20 ACL-R (allo-graft) 20 ACL-D 20 Controls	ACL-D 29.0 (5.4) years 18 men, 2 women ACL-R Auto – 29.5 (6.9) years 20 men Allo – 30.2 (4.6) years 16 men, 4 women	27.6 (2.6) years 17 men, 3 women (plus uninjured knees of patients)	Cybex dynamometer	JPS – from full extension to flexion (no further details given). TTDPM – from 15° flexion to either flexion or extension at an angular velocity of 1°/second	JPS (passive positioning then active repositioning task) – mean angle of error in degrees from 10 trials TTDPM – mean angle of error in degrees from 10 trials randomly assigned to either flexion or extension
Anguoles et al. 2007 [21]	20 ACL-R (hamstring) 20 ACL-R (patella tendon)	16 men, 4 women 18 men, 2 women	N/A	Con-Trex dynamometer	JPS – from full extension (0°) to flexion angles of 15°, 45° and 75°	JPS (passive positioning then active repositioning task) – mean angle of error in degrees from three trials
Mir et al. 2008 [22]	12 ACL-R 12 Controls	23 (4.75) years 12 men	22 (4.35) years 12 men (plus uninjured knees of patients)	Digital camera, markers	From a starting angle of 60° flexion to 30° flexion and from a starting angle of 0° flexion to 30° flexion. All motion was at an angular velocity of 10°/second	JPS (active positioning then active repositioning task) – mean error angle in degrees over 3 trials

ACL-D, patients with an ACL deficiency; ACL-R, patients with a reconstructed ACL; TTDPM, threshold to detect passive motion; JPS, joint position sense; NP, not provided; NA, not applicable.

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Table 2
Methodological quality score for each of the articles included in the meta-analysis.

Scoring section (maximum score)	Barrack *et al.* 2003 [17]	Fischer-Rasmussen and Jensen 1989 [18]	Fremerey *et al.* 2000 [19]	Ozenci *et al.* 2000 [20]	Angoules *et al.* 2007 [21]	Mir *et al.* 2008 [22]
Confirmation of ACL deficiency (3)	3	1	3	1	3	0
Representation of population (19)	9	8	10	14	13	10
Representation of sample (5)	3	0	3	3	3	0
Homogeneity of participants (13)	5	11	11	7	4	11
Sample size (25)	3	9	7	9	6	4
Study design (4)	1	1	1	1	4	1
Assessor blinding/bias (5)	5	0	0	0	5	0
Statistical analysis (14)	1	1	4	3	14	9
Total (88)	30	31	39	38	52	35
Quality level	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate

Notes: Studies were grouped in to poor (a score of less than 29/88), moderate (a score of 30 to 58/88) or good (a score of 59+/88) studies based on their final methodological quality score.

un-injured leg had a lower mean angle of error (better joint position sense) compared to the injured leg (Fig. 1). Four studies compared the injured legs ($n = 140$) to an external control ($n = 104$) [18–21,23]. The pooled standard mean difference of the mean angle of error was 0.35° (95% CI: 0.14 to 0.55; $P = 0.001$; $I^2 = 78\%$) indicating that the control group had better joint position sense than patients with an ACL injury (Fig. 2). Three studies compared ACL reconstructed ($n = 116$) and ACL deficient legs ($n = 100$) [19,21,23]. The pooled standard mean difference of the mean angle error (°) was −0.62° (95% CI: −0.76 to −0.48; $P < 0.001$; $I^2 = 42\%$) indicating that ACL reconstructed patients had better joint position sense (Fig. 3).

Effects of ACL injury on TTDPM

Two studies compared the injured leg ($n = 71$) with the un-injured ($n = 71$) leg in patients with an ACL injury [18,21]. The pooled standard mean difference of mean angle error was 0.02° (95% CI: −0.32 to 0.35; $P = 0.91$; $I^2 = 61\%$) indicating no difference. These studies also compared ACL injured legs ($n = 71$) to external control legs ($n = 30$) which showed a difference in mean angle error of 0.38° (95% CI: 0.04 to 0.72; $P = 0.03$; $I^2 = 73\%$) indicating that the external control group had a better TTDPM than the injured leg group (Fig. 4).

Joint position sense studies and threshold to detect passive motion studies both indicated differences between injured leg and external controls. However, only data collected using the JPS method detected proprioception differences between injured and non-injured legs.

Discussion

This review examined the effect of ACL injury on proprioception, in terms of joint position sense and threshold to detect passive motion. The results cautiously indicate significantly poorer proprioception, in terms of JPS acuity and threshold to detection of movement, in patients with ACL injury compared to their uninjured leg and to people without such injuries. The proprioception of people whose ACL was reconstructed was statistically significantly better than those whose ligament is left unreconstructed (ACL-deficient). These differences are seen whether the comparator group was the patient's uninjured leg, or a control group of people with no injuries; suggesting that either can be used as a control group in future research. The differences in proprioception were seen most clearly when joint position sense was measured but was less consistent when threshold to detect passive motion measurement techniques were used. This indicates that proprioception acuity (measured by joint position sense) may be a greater problem for patients with ACL injuries than TTDMP and should be the priority during proprioceptive rehabilitation.

It is thought that mechanoreceptors in the ACL provide afferent information on the relative position and movement of the knee joint [3,7,24,25] and that ACL injury impairs proprioception by disturbing transmission of this sensory information [5]. Our results give some support to this belief. However, although statistically significant, the differences found were very small (<1°) which is unlikely to be clinically or functionally important. A proprioceptive deficit of at least 5° is thought to be the minimum to indicate a clinically

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Study or Subgroup	ACL Mean	SD	Total	Contra Lateral Leg Mean	SD	Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Angoules (u)	4.13	1.51	20	2.63	1.64	20	2.9%	0.93 [0.28, 1.59]
Angoules (a)	3.98	1.38	20	1.98	0.92	20	2.4%	1.67 [0.94, 2.40]
Angoules (b)	3.9	1.48	20	1.98	0.92	20	2.5%	1.53 [0.81, 2.24]
Angoules (c)	2.43	1.19	20	1.98	0.92	20	3.2%	0.41 [-0.21, 1.04]
Angoules (d)	2.27	0.97	20	1.98	0.92	20	3.2%	0.30 [-0.32, 0.92]
Angoules (e)	3.95	2.2	20	2.2	0.85	20	2.8%	1.03 [0.36, 1.69]
Angoules (f)	3.72	1.5	20	2.2	0.85	20	2.7%	1.22 [0.54, 1.90]
Angoules (g)	2.73	1.4	20	2.2	0.85	20	3.2%	0.45 [-0.18, 1.08]
Angoules (h)	2.47	1.05	20	2.2	0.85	20	3.2%	0.28 [-0.35, 0.90]
Angoules (i)	3.8	1.96	20	2.52	1.1	20	3.0%	0.79 [0.14, 1.44]
Angoules (j)	3.65	1.23	20	2.52	1.1	20	2.9%	0.95 [0.29, 1.61]
Angoules (k)	2.63	1.37	20	2.52	1.1	20	3.3%	0.09 [-0.53, 0.71]
Angoules (l)	2.45	1.2	20	2.52	1.1	20	3.3%	-0.06 [-0.68, 0.56]
Angoules (m)	5.32	2.77	20	2.5	0.7	20	2.6%	1.37 [0.67, 2.06]
Angoules (n)	4.36	1.81	20	2.5	0.7	20	2.6%	1.33 [0.64, 2.02]
Angoules (o)	3.18	1.58	20	2.5	0.7	20	3.1%	0.55 [-0.09, 1.18]
Angoules (p)	2.78	1.23	20	2.5	0.7	20	3.2%	0.27 [-0.35, 0.90]
Angoules (q)	4.73	2.51	20	2.83	0.98	20	2.9%	0.98 [0.32, 1.64]
Angoules (r)	3.97	1.41	20	2.83	0.98	20	2.9%	0.92 [0.27, 1.58]
Angoules (s)	2.82	0.79	20	2.83	0.99	20	3.2%	-0.23 [-0.85, 0.39]
Angoules (t)	2.63	0.86	20	2.83	0.98	20	3.2%	-0.21 [-0.83, 0.41]
Angoules (v)	3.85	1.42	20	2.63	1.64	20	3.0%	0.78 [0.13, 1.42]
Angoules (w)	2.98	1.23	20	2.63	1.64	20	3.2%	0.24 [-0.39, 0.86]
Angoules (x)	2.5	1	20	2.63	1.64	20	3.3%	-0.09 [-0.71, 0.53]
Fischer Rasmussen (a)	3.5	1.37	18	2.7	1.42	18	2.8%	0.56 [-0.11, 1.23]
Fischer Rasmussen (b)	3.1	1.54	18	3.02	0.93	18	2.9%	0.06 [-0.59, 0.71]
Fischer Rasmussen (c)	4.06	1.21	20	3.1	0.79	20	2.9%	0.92 [0.27, 1.58]
Fischer Rasmussen (d)	3.14	1.03	20	3.1	0.9	20	3.3%	0.04 [-0.58, 0.66]
Fremery (a)	6.7	2.2	20	3.6	1.8	20	2.5%	1.51 [0.80, 2.22]
Mir (a)	3.65	2.39	12	4.28	2.08	12	1.9%	-0.27 [-1.08, 0.53]
Mir (b)	3.77	2.04	12	4.13	2.51	12	2.0%	-0.15 [-0.95, 0.65]
Ozenci (a)	4.75	2.15	20	4.54	1.96	20	3.3%	0.10 [-0.52, 0.72]
Ozenci (b)	4.58	1.87	20	4.52	1.55	20	3.3%	0.03 [-0.59, 0.65]
Ozenci (c)	5.3	1.74	20	4.64	1.37	20	3.2%	0.41 [-0.21, 1.04]
Total (95% CI)			660			660	100.0%	0.52 [0.41, 0.63]

Heterogeneity: Chi² = 88.54, df = 33 (P < 0.00001); I² = 63%
Test for overall effect: Z = 9.15 (P < 0.00001)

Std. Mean Difference IV, Fixed, 95% CI — Favours experimental / Favours control

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Study or Subgroup	ACL Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Fischer Rasmussen (b)	3.1	1.54	18	3.22	0.96	20	10.5%	-0.09 [-0.73, 0.54]
Fischer Rasmussen (c)	4.06	1.21	20	3.06	1.18	20	10.2%	0.82 [0.17, 1.47]
Fischer Rasmussen (d)	3.14	1.03	20	3.22	0.96	20	11.1%	-0.08 [-0.70, 0.54]
Fischer-Rasmussen (a)	3.5	1.37	18	3.06	1.18	20	10.4%	0.34 [-0.30, 0.98]
Fremery (a)	6.7	2.2	20	2.2	0.7	20	5.5%	2.70 [1.82, 3.58]
Fremery (b)	3.6	1.7	10	2.2	0.7	20	6.2%	1.21 [0.39, 2.04]
Mir (a)	3.65	2.39	12	3.9	1.77	12	6.7%	-0.11 [-0.92, 0.69]
Mir (b)	3.77	2.04	12	5.49	3.31	12	6.3%	-0.60 [-1.43, 0.22]
Ozenci (a)	4.75	2.15	20	4.54	1.34	20	11.1%	0.11 [-0.51, 0.74]
Ozenci (b)	4.58	1.87	20	4.54	1.34	20	11.1%	0.02 [-0.60, 0.64]
Ozenci (c)	5.3	1.74	20	4.54	1.34	20	10.8%	0.48 [-0.15, 1.11]
Total (95% CI)			190			204	100.0%	0.35 [0.14, 0.55]

Heterogeneity: Chi² = 45.63, df = 10 (P < 0.00001); I² = 78%
Test for overall effect: Z = 3.28 (P = 0.001)

Std. Mean Difference IV, Fixed, 95% CI — Favours ACL Injured / Favours control group

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Study or Subgroup	ACL-R Mean	SD	Total	ACL-D Mean	SD	Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Angoules (b)	3.9	1.48	20	3.98	1.38	20	4.9%	-0.05 [-0.67, 0.57]
Angoules (c)	2.43	1.19	20	3.98	1.38	20	4.1%	-1.18 [-1.86, -0.50]
Angoules (d)	2.27	0.97	20	3.98	1.38	20	3.9%	-1.41 [-2.10, -0.71]
Angoules (f)	3.72	1.5	20	3.95	2.2	20	4.9%	-0.12 [-0.74, 0.50]
Angoules (g)	2.73	1.4	20	3.95	2.2	20	4.7%	-0.65 [-1.29, -0.01]
Angoules (h)	2.47	1.05	20	3.95	2.2	20	4.5%	-0.84 [-1.49, -0.19]
Angoules (j)	3.65	1.23	20	3.8	1.96	20	4.9%	-0.09 [-0.71, 0.53]
Angoules (k)	2.63	1.37	20	3.8	1.96	20	4.6%	-0.68 [-1.32, -0.04]
Angoules (l)	2.45	1.2	20	3.8	1.96	20	4.5%	-0.81 [-1.46, -0.17]
Angoules (n)	4.36	1.81	20	5.32	2.77	20	4.8%	-0.40 [-1.03, 0.22]
Angoules (o)	3.18	1.58	20	5.32	2.77	20	4.4%	-0.93 [-1.59, -0.27]
Angoules (p)	2.78	1.23	20	5.32	2.77	20	4.1%	-1.16 [-1.84, -0.48]
Angoules (r)	3.97	1.41	20	4.73	2.51	20	4.8%	-0.37 [-0.99, 0.26]
Angoules (s)	2.82	0.79	20	4.73	2.51	20	4.2%	-1.11 [-1.78, -0.44]
Angoules (t)	2.63	0.86	20	4.73	2.51	20	4.2%	-1.10 [-1.77, -0.43]
Angoules (v)	3.85	1.42	20	4.13	1.51	20	4.9%	-0.19 [-0.81, 0.43]
Angoules (w)	2.98	1.23	20	4.13	1.51	20	4.5%	-0.82 [-1.47, -0.17]
Angoules (x)	2.5	1	20	4.13	1.51	20	4.0%	-1.25 [-1.93, -0.56]
Fischer Rasmussen (a)	3.5	1.37	18	4.06	1.21	20	4.5%	-0.43 [-1.07, 0.22]
Fischer Rasmussen (b)	3.1	1.54	18	3.14	1.03	20	4.7%	-0.03 [-0.67, 0.61]
Ozenci (a)	4.75	2.15	20	5.3	1.74	20	4.9%	-0.28 [-0.90, 0.35]
Ozenci (b)	4.58	1.87	20	5.3	1.74	20	4.8%	-0.39 [-1.02, 0.24]
Total (95% CI)			436			440	100.0%	-0.62 [-0.76, -0.48]

Heterogeneity: Chi² = 36.03, df = 21 (P = 0.02); I² = 42%
Test for overall effect: Z = 8.85 (P < 0.00001)

Std. Mean Difference IV, Fixed, 95% CI — Favours experimental / Favours control

Figs. 1–3. Forest plots of the comparisons between ACL injury and non-injured knees in studies that measured joint position sense. For brevity only the comparisons which showed significant differences are shown. The letters in brackets following the first authors name refer to subgroups and/or knee motion during proprioception measurement. Angoules (a–x) measured joint position sense data from two reconstruction techniques (hamstring and patella tendon procedures) at three different target angles (15°, 45° and 75°) across four time points (pre-operatively, and 3 months, 6 months and 12 months after surgery). Fischer–Rasmussen (a–d) measured joint position sense in two ACL groups (reconstructed and non-reconstructed) at two different target angles (0° and 60°). Fremerey (a and b) measured joint position sense in two ACL groups (reconstructed and non-reconstructed). Mir (a and b) measured joint position sense in an ACL-reconstructed group at two different target angles (0° and 60°). Ozenci (a–c) measured joint position sense in three different ACL groups (autograft reconstruction, allograft reconstruction and non-reconstructed).

Study or Subgroup	ACL Mean	SD	Total	Control Group Mean	SD	Total	Weight	Std. Mean Difference IV, Fixed, 95% CI	Std. Mean Difference IV, Fixed, 95% CI
Barrack	3.53	1.22	11	2.67	0.84	10	14.5%	0.78 [-0.11, 1.68]	
Ozenci (a)	1.01	0.16	20	1.03	0.91	20	30.3%	-0.03 [-0.65, 0.59]	
Ozenci (b)	0.96	0.27	20	1.03	0.91	20	30.3%	-0.10 [-0.72, 0.52]	
Ozenci (c)	1.93	0.42	20	1.03	0.91	20	24.9%	1.24 [0.56, 1.93]	
Total (95% CI)			71			70	100.0%	0.38 [0.04, 0.72]	

Heterogeneity: Chi² = 10.93, df = 3 (P = 0.01); I² = 73%
Test for overall effect: Z = 2.20 (P = 0.03)

Favours ACL injured   Favours control group

Fig. 4. Forest plot of the comparisons between ACL injury and non-injured knees in studies that measured threshold to detect passive motion comparison. F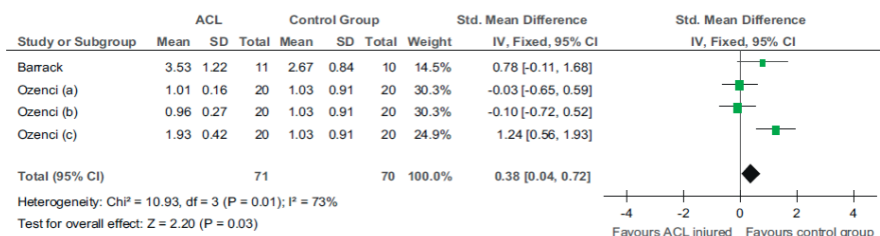or brevity only the comparisons which showed significant differences are shown. The letters in brackets following the first authors name refer to subgroups and/or knee motion during proprioception measurement; Ozenci (a–c) measured threshold to detect passive motion in three different ACL groups (autograft reconstruction, allograft reconstruction and non-reconstructed).

important difference [26] although there is little evidence to support, or refute, this value.

The discrepancy in statistical and functional significance of the proprioceptive differences may be because the measurement techniques were insufficiently accurate to detect clinically significant differences between groups [11] as only one selected study included sufficient information on the psychometrics of the measurement techniques. Therefore the differences in reliability statistics between different JPS equipment and techniques could not be established. We found studies using joint position sense reported greater differences than studies using TTDPM. This may be a consequence of the type of movements tested. TTDPM techniques detect the responses of rapid receptors such as the pacinian capsules in the ACL [5] and would therefore require a more sensitive measurement technique than measures of JPS which measures the slower responses of the ruffini nerve endings and Golgi tendon organs [25].

Another explanation is that the comparisons were underpowered because the sample was too small (none of the included studies calculated sample size using power estimations). However our pooled analysis involved nearly 200 patients and the 95% confidence intervals of the comparisons made were small, indicating that a lack of power was not an issue. Clinicians should be cautious when using knee proprioception techniques without corresponding psychometric properties. Further researcher is needed to evaluate the sensitivity and reliability of techniques to measure proprioception at the knee, before they can meaningfully be used as an evaluation tool in either research or clinical practice.

A more likely, but controversial, explanation for our results is that ACL injury may not have a major impact on proprioception at the knee. This support's the view that muscle, rather than ligaments, provide the primary afferent information in the sensorimotor system [10], which is not surprising given that only 1% of the ACL total area may be made up of proprioceptive receptors and that receptors are often still deficient six months after reconstructive surgery [5]. It may, to some degree, also explain the inconclusive evidence for reconstructive surgery and conservative (non-surgical) rehabilitation [10,27,28]. Joint stability relies on synergy between

muscles and ligaments [1,2,29,30]. Once the ligament is damaged, rehabilitation programmes may help patients adapt by using proprioceptive information from the muscles to compensate for the lack of information from the ligament. Therefore, there may be no restoration of ACL proprioception [20]. This may explain why some patients cope better with ACL injury (however it is managed) than others, some may be more able to make that adaption [5,10,12,27].

A limitation of this meta-analysis is that only English language papers were included. Another limitation is that all data collection was retrospective, which inevitably means that pre-injury proprioception is unknown. It is possible that the patients who suffered injuries had poorer proprioception which predisposed them to injury. Large scale normative studies are needed to give insight into the distribution of proprioception abilities across the population and whether this predisposes people to ACL injury. Such studies should consider a measurement technique that explores the full range of knee motion and direction using large sample sizes that represents the complete ACL patient population and normative data on proprioception ability. A further potential limitation is the high proportion of data provided by a single paper [23] which reported several data sets provided by different methods. Therefore we viewed these as separate studies written as one academic paper. Further research is needed to replicate their findings and to add this to a future meta-analysis.

Heterogeneity of variance was greater than the recommended level of 50% [13] in all but one comparison; this may be due to variability in recruitment strategies and measurement techniques: The time since injury when proprioception was measured ranged from 12 days [20] to over two years [21] and involvement in rehabilitation programmes was inconsistent. Furthermore highly varied measurement techniques were used including three different pieces of equipment and varied knee movements (in terms of direction and speed). This may have hampered the degree to which data could be pooled and as proprioception increases towards the extremes of range of movement (to protect the joint from injury [5,31]), could have contributed to the high levels of heterogeneity. Future research needs to include measurements across the whole range of movement as taking measurements over

specific positions may either under- or over-estimate knee proprioception.

Conclusions

This review examined the effect of ACL injury on proprioception, in terms of joint position sense and threshold to detect passive motion. The results cautiously indicate that patients with ACL injury may have poorer proprioception than an uninjured knee. These differences are seen whether the comparator group is a patient's uninjured leg, or a control group of people with no injuries; suggesting that either can be used as a control group in future research. However, the lack of sufficient data on the psychometric properties of knee proprioception measurement techniques is a major limitation that clinicians or researchers must consider if using knee JPS or TTDPM data during assessment of a rehabilitation programme.

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Conflict of interest: None declared.

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Appendix 1b: The scoring system used in the Meta-Analysis

Authors	
Article Title	
Source	
Years/Volume/Pages	
Institute affiliation & Contact address	

Do not proceed if one of the following six categories is not adhered to:-

	Yes
Human Study	
English Language	
All participants adults / teenagers	
Were all subjects ACL deficient and/or reconstructed or acting as a healthy control group?	
Were ACL participants categorised into ACL-D, ACL-R or ACL-R pre and post op?	
Was at least one OM a direct measure of proprioception, either TTDPM or JPS?	

POPULATION

A. Confirmation of ACL Deficiency

Was ACL deficiency confirmed by:

	Score
Not stated	0
Arthroscopy or MRI OR clinical examination using Lachmans, pivot shift test or knee arthrometer	1
Arthroscopy or MRI AND clinical examination using Lachmans, pivot shift test or knee arthrometer	3

B. Representation of Population

Were the ACL participants classified into -

	Score
A sub-group of deficient or reconstructed patients recruited (e.g. those who are undergoing or have completed rehab or copers/ non-copers/ adapters, or limited by age, sex, activity)	1
ACL deficient or ACL reconstructed groups only	3
People with all types of ACL problem (deficient and reconstructed)	5

Were ACL-R classified according to:

	Yes	No
Type of surgery stated	1	
Type and number of complications stated	1	
Same surgeon for every ACL-R participant	1	
Assessment of laxity pre and post-surgery	1	

Did any ACL participant (ACL-D or ACL-R) have any of the following:- If authors do not mention a previously reconstructed ACL assume the answer is 'no'.

	Yes	No
Previous Injury to ACL Knee		2
Concurrent damage to ACL knee during ACL injury		2
Injury to the ankle or hip on ACL injury side		2
Injury to contralateral leg		2
Rehabilitation prior to the point of assessment		2

C. Representation of Sample

Was the recruitment strategy -

	Score
Not stated in the text	0
Stated in the text	1
Based on convenience sampling (e.g. physio department, surgical list, sports club)	3

Based on comprehensive sampling (e.g. recruitment of ACL-D and ACL-R across different populations)	5

D. Homogeneity of Participants

Was a control comparison used?

	Score
No	0
Contralateral leg	1
Separate control group (true control)	3

Were the following factors *similar or comparable* between the controls and ACL injury group?

	True Control	Contralateral Knee
Age	2	1
Sex	2	1
Pre-injury levels of activity	2	1

E. Sample Size

Was a justification of sample size given (power calculation or accuracy/minimal detectable difference of the measurement tool)?

Yes	No
10	0

Were the numbers of participants between:-

Number of participants in each group	Control Group	ACL injury group 1	ACL injury group 2	Score
0-5				0
6-10				1

11-15				2
16-20				3
21-25				4
>26				5
TOTAL				

METHODOLOGICAL QUALITY

F. Study Design

Was the study design clearly described?

Yes	No
1	0

Was the data collection -?

	Yes
Retrospective	0
Prospective	3

G. Assessor Blinding / Bias

Were the outcome assessors blind to the type of participants?

Yes	No
5	0

H. Statistical Analysis

Were the correct statistics used for data analysis in accordance to the type of data collected (i.e. parametric/ non-parametric)? NOTE: if parametric tests were used, was normality of the data assessed?

Yes	No / no statistics used
5	0

Was the level of significance appropriate and analysis correctly interpreted? -

No	0
Level was appropriate only	1
Level was appropriate and correct interpretation was made	3

Were the OMs tested for inter-tester and test-retest reliability?

	Score
No evidence of reliability testing	0
Reliability was reported using results from external studies	1
Yes, reliability tested within the study and ICC / Kappa yielded good results (>.07)	3

Were the OMs tested for sensitivity to change?

	Score
No evidence of sensitivity to change testing	0
Sensitivity to change was reported using results from external studies	1
Yes, effect size / MDC yielded good results (>.07)	3

TOTAL SCORE: */88*

Appendix 1c: The characteristics of studies excluded from the meta-analysis

Studies concluding ACL injury does reduce knee joint position sense.

Study	Design	Participants	Rebab?	Equipment	JPS Method and Outcome Measures	Reliably or Validity Statistics?	Results
Carter *et al.*, (1997)	ACL-D JPS Cross Sectional Study.	50 ACL-D (Servicemen).	Yes	Isokinetic dynamometer.	Passive- Visual Analogue Scale JPS. Target angle "between 0°-90°". Absolute mean error score (°)	No	JPS impaired in ACL-D knee compared to contralateral knee.
Rehm *et al.*, (1998)	Comparison study of ACL-D copers, ACL-D non-copers and control.	17 Control, 10 ACL-D copers, 20 ACL-D non-copers.	N/S	Purpose built proprioception device.	Passive-Visual Analogue Scale JPS. From 0° to 10°-60°. Absolute mean error score (°)	No	Non-copers had significant higher error scores than two other groups.
Katayama *et al.*, (2004)	Relationship study between proprioception and performance.	32 ACL-D (17M, 15F, mean 25.6yr).	Yes	Biodex Machine	Passive – Passive (hold button) JPS. From 90° to 85° - 65° at 10°/s. Absolute mean error score (°)	No	JPS impaired in ACL-D knee compared to contralateral knee.
Barrett (1991a)	ACL-D JPS Cross Sectional Study.	10 ACL-D, 45 ACL-R (33M, 12F, mean 26.4 years), 20 Control.	Yes	Modified Thomas Splint as Proprioception device (no motor).	Passive – Visual Analogue Scale JPS. No other details. Absolute mean error score (°)	No	ACL-D knees impaired when compared to ACL-R and Control.
Ochi *et al.*, (1999)	Cross-sectional study of JPS in ACL-D, ACL-R and Controls. JPS taken pre and post-surgery.	32 ACL-D (16M, 16F, mean 25.5years), 23 ACL-R (13M, 10F, mean 27.8years) and 14 Control (9M, 5F, mean 22.9 years).	N/S	No detail of Proprioception device.	Passive-Active JPS. From 90° to 5°-25° at approximately 10°/s. Absolute mean error score (°)	No	ACL-D knees impaired when compared to ACL-R and Control.
Wada *et al.*, (2002).	Cross-sectional comparison study of JPS in ACL-R (total knee arthroscopy) and controls.	38 ACL-R (3M, 35F, mean 72.6years). 23 Controls (2M, 21F, mean71.5 years).	N/S	Electro-goniometer	Active-Active JPS. From 90° to 60° to 40°. Absolute mean error score (°)	ICCs.	ACL-R knee impaired when compared to controls.

Iwasa *et al*., (2000).	Longitudinal design measuring JPS across 24 months post-surgery.	38 ACL-R (18M, 20F, mean 28.4 years).	Yes	Cybex II Dynamometer.	Passive-Active JPS. From 90° to 85°-65° at approximately 10°/s. Absolute mean error score (°)	No	JPS was significantly improved following 18, 21 and 24 months of rehab compared to pre-operative levels.
Fremerey *et al*., (2001)	Longitudinal comparison of JPS in 2 surgical reconstruction techniques used on ACL-R patients.	29 ACL-R. 15 endoscopic (8M, 7F, mean 25.8yrs). 14 open (8M, 6F, mean 27.3yrs).	Yes	Purpose built proprioception device.	Passive-Passive JPS. From 0° to 0°-20° , 40° -60° or 80° -100° at 0.5° /s. Absolute mean error score (°)	Accuracy device reading of 0.1°.	Pre-operative all ACL-R knees impaired compared to uninjured side. 3 months all ACL-R knees impaired compared to uninjured side. 6 months & 4yrs all ACL-R knees impaired compared to uninjured in mid-range only.
Zhou *et al*., (2008)	Longitudinal comparison of ACL-D and controls.	36 ACL-R (30M, 6F, mean 26years). 13 Controls (11M, 2F, mean 26.4years).	Yes	Biodex system 3.	Passive-Passive (hold button) JPS. From 0° to 0°-20° , 40° -60° or 80° -100° at 0.5° /s. Absolute mean error score (°)	No	ACL-R knee impaired when compared to controls.
Baumeister *et al*., (2008)	Cross-sectional comparison study of JPS in ACL-R and controls.	10 ACL-R (7M, 3F, mean 27years, 181cm, 76kg). 12 controls (9M, 3F, mean 25years, 181cm, 76kg).	Yes	Electro-goniometer.	Active-Active JPS. From 90° to 40°. Absolute mean error score (°)	No	ACL-R knee impaired when compared to controls.

Studies concluding ACL injury does not reduce knee joint position sense.

Study	Design	Participants	Rebab?	Equipment	JPS Method and Outcome Measures	Reliably or Validity Statistics?	Results
Remedios *et al.*, (1998)	Cross-sectional comparison study of ACL-R and Controls.	28 ACL-R (28F, 25 years), 28 Controls (28F, 23 years)	Yes	Electro-goniometer.	Passive-Active JPS (match angle with contralateral leg, ACL-R leg passive, contralateral active.) From 90° to 15° or 60°. Absolute mean error score (°)	Device was within 2° of accuracy	No difference in JPS between ACL-R and Controls.
Good *at al.*, (1999)	Cross-sectional JPS study on ACL-D patients.	18 ACL-D (10M, 8F, median 28years).	N/S	Electronic tilt sensors.	Passive-active and active-active JPS (passive or active move from 0° to 30° or 70°) Real and absolute error score (°)	Accuracy of tilt was <0.1°.	No differences in JPS between ACL-D knee and contralateral control.
Harter *et al.*, (1992)	Cross-sectional JPS study on ACL-R patients.	48 ACL-R (30M, 18F, 28years).	N/S	Cybex Dynamometer	Passive-Active JPS. From 90° to 15 - 30° at 10-15°/s). Absolute mean error score (°)	No	No differences in JPS between ACL-R knee and contralateral control.
Hopper *et al.*, (2003)	Cross-sectional JPS study on ACL-R patients.	9 ACL-R (5M, 4F mean 29.3years).	N/S	Peak motion system. Video Camera.	Active – active JPS. From 30°-40° to 0-30° flexion or extension. Absolute mean error score (°)	No	No differences in JPS between ACL-R knee and contralateral control.
Dvir *et al.*, (1988)	Cross-sectional JPS study on ACL-R patients.	25 ACL-R (21M, 4W) Aged 17-37years.	N/S	Purpose built proprioception device.	Passive-Passive JPS and Passive-Active JPS from 90° and 0° 20°-40° and 50°-70°. Absolute mean error score (°)	No	No differences in JPS between ACL-R knee and contralateral control.

Studies concluding ACL injury does reduce threshold to detect passive motion.

Study	Design	Participants	Rebab?	Equipment	TTDPM Method and Outcome Measures	Reliability and Validity Statistics?	Results
Valeriani *et al.*, (1999).	Cross-sectional comparison of ACL-R pre and post-surgery.	19 ACL-R (mean 28years). 15 Controls (8M, 7F, mean 29years).	N/S	Purpose built proprioception device.	TTDPM from 40°. Distance before detection (°)	No	ACL-R had decreased TTDPM ability 4years after surgery.
Borsa *et al.*, (1997)	Cross-sectional comparison of ACL-R to contralateral knees.	29 ACL-D (15M, 14F, mean 28.7years).	Yes	Purpose built proprioception device.	TTDPM from 15° and 45° into flexion and extension at 0.5°/s. Distance before detection (°)	ICCs	ACL-R had decreased TTDPM ability compared to contralateral knee.
Beynnon *et al.*, (1999)	Cross-sectional comparison of ACL-D to contralateral knees.	20 ACL-D (13M, 7F, mean 40years).	N/S	Purpose built proprioception device.	TTDPM from 45° into flexion or extension. Distance before detection (°)	No	ACL-D had decreased TTDPM ability compared to contralateral knee.
Friden *et al.*, (1999)	Cross-sectional comparison of ACL-D to contralateral knees and external controls.	16 ACL-D (11M, 5F, mean 26years)	Yes	Purpose built proprioception device.	TTDPM from 20° and 40° into flexion and extension at 0.5°/s.	CIs	ACL-D had decreased TTDPM ability compared to contralateral knee and controls.

					Distance before detection (°)		
Courtney *et al*., (2005)	Cross-sectional comparison of ACL-D to contralateral knees and external controls.	17 ACL-D (7M, 10F, mean 34.5years), 7 Control (1M, 6F mean 27years).	N/S	Purpose built proprioception device	TTDPM from 40° at 0.5°/s. Distance before detection (°)	No	ACL-D had decreased TTDPM ability compared to contralateral knee and controls.
Courtney *et al*., (2006)	Cross-sectional comparison of ACL-D to contralateral knees.	15 ACL-D (5M, 10F, 34 yrs). 7 Control (26 years).	N/S	Purpose built proprioception device.	TTDPM from 40° into flexion at 0.5°/s. Distance before detection (°)	No	ACL-D had decreased TTDPM ability compared to contralateral knee.
Ageberg *et al*., (2005)	Correlation study between laxity, proprioception, and muscle strength in ACL-D.	36 ACL-D (18M, 18F, mean 26years).	Yes	Purpose built proprioception device.	TTDPM 20° and 40° into flexion and extension at 0.5°/s. Distance before detection (°)	No	Poor TTDPM and high muscle strength were associated with low average speed in women. Low amplitude correlates with better function.
MacDonald *et al*., (1996)	Cross-sectional comparison of ACL-D to ACL-R and external controls.	10 ACL-D, 16 ACL-R, 6 Control	Yes	Dynamometer	TTDPM from 30°-40°at 0.5°/s. Distance before detection (°)	No	ACL-D and ACL-R had decreased TTDPM ability compared to contralateral knee.

Lephart *et al*., (1992)	Cross-sectional comparison of ACL-D to contralateral knees.	12 ACL-R (4M, 8F, mean 23.3years).	Yes	Purpose built proprioception device.	TTDPM from15° and 45 at 0.5°/s. Time before detection (°)	Test – re-test Reliability of device (*r* = 0.92)	ACL-R had decreased TTDPM ability compared to contralateral knee.
Valeriani *et al*., (1996)	Cross-sectional comparison of ACL-D to external controls.	7 ACL-R.	N/S	Purpose built proprioception device	TTDPM from 40° into flexion. Distance before detection (°)	No	ACL-R had decreased TTDPM ability compared to controls.

Studies concluding ACL injury does not reduce threshold to detect passive motion.

Study	Design	Participants	Rebab?	Equipment	Outcome Measures	Error?	Results
Risberg *et al*., (1999)	Comparison study of TTDPM between ACL-D and controls.	20 ACL-R (8M, 12F, 35yr), 10 controls (5M, 5F, 33yr).	Yes	Purpose built proprioception device.	TTDPM from 15° into flexion or extension at 0.5°/s.	No	No TTDPM differences between groups or knees.
Pap et al., (1999)	Comparison study of TTDPM between ACL-D and controls.	20 ACL-D (14M, 6F, mean 24.5yrs).15 Control (mean 25.3 years).	No	KT-1000 arthrometer, purpose built proprioception device.	Threshold for perception of start of movement (TPSM, °) and Threshold for perception of end of movement (TPEM, °) From 45°.	No	No TTDPM differences between groups.

Studies investigating the effect of ACL injury on both JPS and/or threshold to detect passive motion.

Study	Design	Participants	Rebab?	Equipment	Methods and Outcome Measures
Corrigan *et al*., (1992)	Correlation between proprioception and muscle strength.	20 ACL-D (mean 30years). 17 Control (17M, mean 28years)	No	Purpose built proprioception device.	TTDPM at 0.3°/s. Distance before detection (°) Passive-Active JPS. From 35° at 10°/s. Absolute mean error score (°)
Friden *et al*., (1996)	Cross-sectional comparison study of proprioception on ACL-D and controls, specifically in the nearly extended knee.	19 control (14M, 5F, mean 25years), 20 ACL-D (14M, 6F, mean 26years).	N/S	Purpose built proprioception device.	TTDPM from 20° and 40° to flexion and extension at 0.5°/s. Distance before detection (°) Passive-Visual Analogue Scale JPS From 60° into 30° of flexion and 30° to 30° of extension at 0.5°/s. Passive-Active JPS

					From 60° into 30° of flexion and 30° to 30° of extension at 10°/s. Absolute mean error score (°)
Friden *et al*., (1997)	Longitudinal study of proprioception and ACL-R.	16 ACL-R (11M, 5F, mean 26years)	Yes	Purpose built proprioception device	TTDPM from 20° and 40° to flexion and extension at 0.5°/s. Distance before detection (°) Passive-Visual Analogue Scale JPS From 60° into 30° of flexion and 30° to 30° of extension at 0.5°/s. Passive-Active JPS From 60° into 30° of flexion and 30° to 30° of extension at 10°/s. Absolute mean error score (°)
Roberts et al., (1999)	Cross-sectional study on proprioception in ACL-R.	17 ACL-D (Copers) (10M, 7W mean 28.8years), 20 ACL-D (Non-copers) (14M, 6W mean 26.6years).	Yes	Purpose built proprioception device.	TTDPM from 20° and 40° to flexion and extension at 0.5°/s. Distance before detection (°)

					Passive-Visual Analogue Scale JPS From 60° into 30° of flexion and 30° to 30° of extension at 0.5°/s.
					Passive-Active JPS From 60° into 30° of flexion and 30° to 30° of extension at 10°/s. Absolute mean error score (°)
Roberts *et al*., (2000)	Cross-sectional comparison of proprioception in ACL-D, ACL-R and Controls.	20 ACL-R (15M, 5F, mean 27years). 19 Controls (14M, 5F, mean 25years).	Yes	Purpose built proprioception device.	TTDPM from 20° and 40° to flexion and extension at 0.5°/s. Distance before detection (°) Passive-Visual Analogue Scale JPS From 60° into 30° of flexion and 30° to 30° of extension at 0.5°/s. Passive-Active JPS From 60° into 30° of flexion and 30° to 30° of extension at 10°/s.

					Absolute mean error score (°)
Reider *et al*., (2003)	Longitudinal study comparing proprioception before and after ACL Reconstruction.	26 Controls (18M, 13F, 25years) ACL-R (15M, 11F 25years).	Yes	Electro-goniometer.	TTDPM from 15° flexion to flexion or extension at 3°/s. Distance before detection (°) Passive Active JPS from full extension. Absolute mean error score (°)
Muaidi *et al*., (2009)	Comparison study of proprioception in the transverse plane between ACL-D, ACL-R and controls.	20 ACL-R (14M, 6F, 30years) and 20 Controls (14M, 6F, 29years).	Yes	Purpose built proprioception device.	Passive identification of joint angle (just-noticeable difference JND),
Bonfim *et al*., (2003).	Comparison of proprioception in ACL-R and controls.	10 ACL-R (7M, 3F, mean 24.4 years). 10 Control (7M, 3F, mean 24.4years).	Yes	Purpose built proprioception device.	TTDPM Distance before detection (°) Passive-Visual Analogue Scale JPS Absolute mean error score (°)

Studies concluding ACL injury does not reduce JPS and/or threshold to detect passive motion.

Study	Design	Participants	Rehab?	Equipment	Methods and Outcome Measures	Reliability and Validity Statistics?	Results
Wright *et al*., (1995)	Cross-sectional comparison study between ACL-D and control group.	8 ACL-D and 1 ACL-R, 15 Control.	N/S	Purpose built proprioception device	TTDPM from 40° into flexion at 0.5°/s 5°/s. Distance before detection (°)	No	No significant differences between ACL group and control or other knee.
Fischer-Rasmussen *et al*., (2001).	Reliability of TTDPM and JPS in Controls and proprioception of ACL-Deficient.	15 controls (mean 27.7years) 10 ACL-D (6M, 4F mean 27.3years).	No	Purpose built proprioception device.	TTDPM from 20° at 0.5°/s. Distance before detection (°) Passive – active JPS. From 25° to15°, 25°, 35° or 60°. Active- Active JPS. From 60° to 5° of flexion at 0.5°/s with 20% MVC. Absolute mean error score (°)	CoV	No significant differences between ACL-D injured and non-injured side.

Jensen *et al*., (2002)	Cross-sectional comparison study of proprioception with ACL-D copers and ACL-D non-copers.	7 ACL-D copers (6M, 1F, mean 31.1years), 7 ACL-D non-copers (3M and 4F, mean 30.1years).	N/S	Purpose built proprioception device.	TTDPM from 20° at 0.5°/s. Distance before detection (°) Passive-active JPS. From 60° into 35°, 25°, 15° of flexion. Passive-passive JPS without muscle tension (vel 5°/s), Active-active JPS (20% or 50% MVC). Absolute mean error score (°)	No	Majority of differences between ACL-D group and control group in proprioception variables were non-significant.
Co *et al*., (1993)	Comparison of knee proprioception and heel strike transient between ACL-R and controls.	10 ACL-R (5M, 5F, mean 27 years. 10 Controls (5M, 5F, mean 24years).	Yes	Purpose built proprioception device. Force plate. Isokinetic Dynamometer.	TTDPM at 0.5°/s.Distance before detection (°) Passive-passive (contralateral leg) JPS	No	Majority of differences between ACL-R group and control group in proprioception variables were non-significant.

					from 40° to 10°,20°,25° of motion. Passive-active JPS from 40° to 5°-25° of motion. Absolute mean error score (°)		
Nishiwaki *et al*., (2007)	Relationship between muscular strength after ACL-R.	16 ACL-R (6M, 10F, mean 28years, 163,6cm, 62.9kg).	Yes	Isokinetic Dynamometer.	TTDPM from 15° and 45° at 0.5°/s. Distance before detection (°) Passive-Passive JPS (hold button) from 90° to 5°, 10°, 15°, 20°, 25° and 30° of extension at 10°/s. Absolute mean error score (°)	Accuracy 0.28°. Mean variation of 6.1 3.4°, CIs	No significant differences between ACL-D injured and non-injured side.
Fonseca et al., (2005).	Cross-sectional comparison of proprioception between ACL-D and controls.	11 ACL-D (9M, 2F, mean 26.45years). 11 Controls (9M 2F, mean 27.35 years)	Yes	Isokinetic dynamometer.	TTDPM from 35° into extension at 2°/s. Time before detection (°)	No	No significant differences between groups.

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					Passive-Passive (hold button) JPS. From 90° to 35°at 10°/s. Passive-Active JPS Absolute mean error score (°)		

Appendix 1d: Inter-examiner, intra-examiner and test-retest reliability of clinical knee joint position sense measurements using an image capture technique.

Inter-examiner, intra-examiner and test-retest reliability of clinical knee joint position sense measurements using an image capture technique.

Context: Knee joint position sense (JPS) plays a critical role in controlled and stable joint movement. Poor ability to sense position of the knee can therefore increase risk of injury. There is no agreed consensus on JPS measurement techniques and a lack of reliability statistics on methods. *Objective*: To identify the most reliable knee JPS measurement technique using image capture. *Design*: Inter-examiner, intra-examiner and test-retest reliability of knee JPS measurements. *Setting*: Biomechanics laboratory. *Participants*: Ten asymptomatic participants. *Interventions*: None. *Main Outcome Measures:* Relative and absolute error scores of knee JPS in three conditions (sitting, prone, active) through three ranges of movement (10-30°, 30-60°, 60-90°), into two directions (flexion and extension) using both legs (dominant and non-dominant) collected during 15 trials and repeated seven days after the first data collection. *Results:* Statistical analysis by intraclass correlations revealed excellent inter-examiner reliability between researchers (0.98) and intra-examiner reliability within one researcher (0.96). Test-retest reliability was highest in the sitting condition from a starting angle of 0°, target angle through 60°-90° of flexion, using the dominant leg and AES variables (ICC = 0.92). However, it was noted smallest detectable differences (SDDs) were a high percentage of mean values for all measures. *Conclusions:* The most reliable JPS measurement for asymptomatic participants has been identified. Practitioners should use this protocol when collecting JPS data during pre-screening sessions. However, generalizability of findings to a class/group of clients exhibiting knee pathologies should be done with caution.

Joint position sense (JPS) is defined as the static awareness of limb position in space[1]. Poor knee JPS may result in an increased risk of injury[2]. The use of JPS in a clinical setting is used to identify patients that may be more at risk of injury due to poor JPS ability[3]. It is vital clinicians are confident the data is reliable and results are not masked by measurement error.

Practitioners use a range of equipment to measure JPS, such as isokinetic dynamometer[1], however, this is not considered the most viable or reliable equipment to measure knee JPS[3]. Other techniques include image capture and electrogoniometery[1]. A review[3] evaluated the reliability of these knee joint position assessment methods and concluded reliability was highly variable between all techniques. Each method may measure a different aspect of JPS therefore techniques should not be used interchangeably. However, image capture techniques appear to have the highest feasibility and most consistent knee JPS results[3].

In addition to equipment selection, JPS protocols must also be considered. The most common method of JPS is that of the passive position of a target angle then active reposition to identify knee JPS ability[4]. There are additional variables to consider, such as position of the patient, selected starting and target angles and direction of movement. Previous studies have yielded conflicting results regarding the most representative JPS protocol, due to the apparent inconsistencies in methodological details. For example it has been suggested weight-bearing closed chain tests are more ecologically valid than non-weight-bearing open chain tests as they provide maximal afferent information from adjacent joints and structures[5]. However, not all literature produced optimal JPS performance in weight-bearing conditions[6]. Given the total number of variables practitioners must consider when selecting

a JPS protocol it is unsurprising that a comprehensive reliability analysis is absent from the literature. There is a need for a study to consider a large range of dependent variables with the same participants[3]. It is stated "*while the importance of proprioception as a clinical outcome measure is becoming well recognised, the best measurement techniques have yet to be define*"[4] (p.128). There is no previous data on the reliability of JPS measurement using image capture within a range of protocols. Therefore the aim of the current study is to identify the most reliable, in terms of test-retest, intra-examiner and inter-examiner, knee JPS measurement technique using image capture equipment.

Methods

Using a repeated measures design, ten participants (age 30.2±8.87years, mass 71.5±18.30kg, height 1.71±11.23m, Tegner 5.3±2.50) took part in the study. All were free from lower extremity injury and neurological disease. Participants provided written informed consent and the study was approved by institutional research ethics committee.

Procedures

Markers were placed on anatomical points; a point on a line following the greater trochanter to the lateral femoral epicondyle, close to the lateral femoral epicondyle, the lateral femoral epicondyle and the lateral malleolus of both legs. Testing was conducted in three conditions, sitting, prone and active. The sitting and prone conditions took place on an orthopaedic plinth with the participant blindfolded. Each leg was passively moved through either 10°-30°, 30°-60° or 60°-90° of knee flexion (from a starting angle of 0°) or knee extension (from a starting angle of 90°) to a randomized target angle at an angular velocity of approximately 10°/s. The participant was instructed to focus on the position of the knee and actively hold

the leg in this position for 5s. A photograph of the leg was taken using a camera (Casio Exilim, EX-FC100, Casio Electronics Co.,Ltd. London, UK) placed 3m from the sagittal plane of movement on a fixed level tripod (Camlink TP-2800, Camlink UK, Leicester, UK). The leg was then passively returned to the starting angle and the participant was instructed to actively move the same leg to the target angle and hold the leg in this position whilst another photograph was taken.

For the active condition, the participant was positioned supine on a "Total Trainer" (Model TT2500P, Bayou Fitness, Louisiana, USA; see Figure 1) and blindfolded. The equipment was set at level 1 incline, providing 10% body weight (BW) resistance. Each leg was actively moved to the same random order range of target angles as in the previous conditions using the sliding seat on the "Total Trainer" at approximately 10°/s. The participants were instructed to actively contract into flexion or extension until verbally told to stop by the experimenter and hold that position for 5s whilst a photograph was taken. The participant then returned the leg to the starting position and was instructed to actively move the same leg to the target angle without verbal cues. Another photograph was taken. The process was repeated 15 times for each target angle on both dominant and non-dominant legs in all three conditions. The protocol was repeated seven days later.

FIGURE 1 NEAR HERE

Analysis

Knee angles were measured using open access digitizing software (ImageJ, U. S. National Institutes of Health,, Maryland, USA, http://imagej.nih.gov/ij/, 1997-2013). Knee JPS was calculated from the average delta scores between target and reproduction angles across 15 trials, producing real (magnitude and direction) error scores (RES) and absolute (magnitude only) error scores (AES) [4].

Statistical analysis used SPSS (Version 19, IBM Corporation, New York, USA). The Shapiro-Wilk test examined normality of data, which was confirmed. Inter-examiner and intra-examiner reliability was confirmed using intra-class correlation coefficients (ICC 2, 1), 95% Confidence Intervals and Cronbach's Alpha[7]. A randomly selected data set of 30 trials was analysed by the researcher and then by an independent rehabilitation practitioner. The researcher repeated the analysis of the randomly selected data set of 30 trials.

Test-retest reliability was assessed using intra-class correlation coefficients (specifically ICC, 3, 1). Standard Error Mean (SEM) (standard deviation x (95% Confidence Intervals (CIs) (1.96xSEM) and Smallest Detectable Difference (SDD) (1.96x. ICC results greater than 0.75 are excellent, between 0.40-0.75 are modest and less than 0.40 are poor[8].

Results

The ICC value corresponding to inter-examiner reliability was 0.98 and 95% CIs ranged from 0.96-0.99. Cronbach's Alpha value was 0.99. The ICC value for intra-examiner reliability was 0.96 and 95% CIs ranged from 0.91-0.98. Cronbach's Alpha value was 0.98.

Tables one-three display all data. ICCs ranged from 0.03-0.80 in RES data and 0.65-0.92 in AES data in the sitting condition. In the prone condition ICCs ranged from 0.53-0.79 in RES data and 0.27-0.90 in AES data. For the active condition ICCs ranged from -0.18-0.89 in RES data and-0.13-0.82 in AES data. Furthermore, SDDs ranged from 2.26°-5.48° in RES data and 1.10°-2.45° in AES data in the sitting condition. In the prone condition SDDs ranged from 2.37°-8.71° in RES data and 1.65°-8.37° in AES data. For the active condition SDDs ranged from 0.85°-5.39° in RES data and 1.23-3.14 in AES data. The results indicated the test of knee JPS with the highest ICC value is the sitting condition from a starting angle of 0°, target angle through 60°-90°of flexion, using the dominant leg and calculating absolute error scores.

Tables 1-3 near here

Discussion

This is the first study to comprehensively consider reliability of knee JPS using image capture data acquisition techniques. The inter-examiner reliability results were "excellent" indicating it may be appropriate for different practitioners to analyze images collected during

JPS testing. The test-retest reliability results indicate a large range of ICCs. The highest ICC score and hence "excellent" reliability measure of knee JPS was tested in a sitting condition, dominant leg, from a starting angle of 0°, into flexion through 60°-90° of movement, calculating absolute error scores (ICC=0.92). Practitioners should adopt the techniques with "excellent" levels of test-retest reliability when using JPS to screen asymptomatic populations.

The sitting condition provided the most reliable position for JPS data collection, 11 out of 24 JPS measurements had "excellent" ICC scores. However, the active condition presented the poorest level of test-retest reliability, with only two out of 24 measures producing "excellent" test-retest reliability results. It has been suggested active positioning-active repositioning weight-bearing JPS measures may illicit maximum JPS performance due to an increase of mechanoreceptor activity across the kinetic chain[9]. However, authors have criticised weight-bearing conditions as it is not a true representation of isolated knee JPS[10]. Therefore we aimed to create a "semi-weight bearing" condition in which the participant was under 10% body weight in order to increase ecological validity, but still isolate knee joint proprioceptors by minimizing movement in adjacent joints. However, the motor control needed to complete this procedure may require greater learning time before data collection begins. Longer practice sessions and also individualised loading rates may be necessary to ensure participants are accustomed to this JPS protocol.

Results suggest absolute error scores were more consistent than relative error scores in all three conditions. Therefore practitioners should use absolute error scores in asymptomatic JPS testing. This is perhaps unsurprising due to the additional dimension provided by

relative error scores (direction of error), consistency is harder to attain. There is little evidence to suggest direction in which the error occurs will influence an increased injury risk. For example we do not know if over estimating the position of a limb in any worse than underestimating. It has also been suggested average relative error scores mask JPS ability, as the average of repeated trails can incorrectly reduce the error score[11]. Therefore, it is appropriate to use magnitude of error (AES) only in JPS testing.

An important finding in this study was the high SDD scores within all JPS measurements. The most reliable measurement had a SDD value which was 34% of the AES and some SDDs were more than the mean scores. To our knowledge SDD scores for JPS testing using image capture techniques have not been previously reported. Previous research[12] reported standard error of measurement values of up to 50% of the mean knee JPS error score, however testing was completed using a perturbation protocol not reproduction of an angle as in the current study. Future studies need to confirm SDD values so practitioners can be confident athlete progression in screening programmes is not masked by measurement error.

A limitation of this study is the sample did not include symptomatic patients. Therefore results should not be generalized to knee pathology groups. Future research should collect normative JPS data from both uninjured and injured populations. However, practitioners should use the results to review reliability of their chosen knee JPS measurement technique. It is suggested a method that seats the patient, uses a starting position of 0°, through flexion to a target angle between 60°- 90° will yield the highest test-retest

reliability data. It is also recommended AES be used rather than relative error scores to collect consistent data. However, practitioners should consider the high SDD figure if using measurements of knee JPS in longitudinal screening. It may be that measurement error masks true improvement of JPS acuity. The results of this study indicate the type of JPS protocol using image capture techniques that provide excellent reliability are in a sitting position, passive then active knee positioning to a target near the end range of movement at approximately 10°/s.

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Figure 1. The Total Trainer Model TT2500P, Bayou Fitness, Louisiana, USA

Table 1. Mean (°), standard deviation (SD), 95% confidence intervals (CI), standard error of measurement (SEM), smallest detectable difference (SDD) and intraclass correlation coefficient (ICC) values in a sitting condition.

Relative Error Scores (RES)								
Test	Mean[1]	SD[1]	Mean[2]	SD[2]	ICC	95% CI	SEM	SDD

	Mean¹	SD¹	Mean²	SD²	ICC	95% CI		SEM	SDD
Dominant Leg									
Extension 10°-30°	2.0	1.20	2.4	1.18	0.54	-0.08	0.86	0.82	2.26
Extension 30°-60°	2.0	1.83	1.5	2.25	0.78	0.36	0.94	0.96	2.65
Extension 60°-90°	-0.1	1.50	-0.3	2.06	0.80	0.38	0.95	0.83	2.31
Flexion 10°-30°	-0.8	1.88	-1.2	1.27	0.03	-0.65	0.63	1.58	4.38
Flexion 30°-60°	-1.0	1.83	-2.0	1.91	0.67	0.09	0.91	0.94	2.59
Flexion 60°-90°	-1.7	1.53	-0.8	2.20	0.40	-0.20	0.80	1.45	4.02
Non-dominant Leg									
Extension 10°-30°	2.4	1.77	2.1	2.24	0.75	0.27	0.93	1.04	2.87
Extension 30°-60°	1.9	1.64	1.2	2.09	0.66	0.15	0.90	1.05	2.91
Extension 60°-90°	0	1.46	0	1.72	0.51	-0.18	0.86	1.14	3.17
Flexion 10°-30°	-0.2	1.83	-0.8	1.57	0.62	0.08	0.89	1.01	2.81
Flexion 30°-60°	-2.1	3.11	-2.1	1.79	0.58	-0.07	0.88	1.68	4.66
Flexion 60°-90°	0.2	2.72	-0.9	2.00	0.30	-0.31	0.76	1.98	5.48
Absolute Error Scores (AES)									
Test	**Mean¹**	**SD¹**	**Mean²**	**SD²**	**ICC**	**95% CI**		**SEM**	**SDD**
Dominant Leg									
Extension 10°-30°	2.5	1.09	2.5	1.06	0.76	0.26	0.93	0.55	1.53
Extension 30°-60°	2.6	1.49	2.4	1.63	0.86	0.54	0.96	0.60	1.67
Extension 60°-90°	1.7	0.89	2.1	0.98	0.70	0.20	0.91	0.49	1.35
Flexion 10°-30°	2.3	1.05	2.4	0.97	0.79	0.37	0.94	0.47	1.31

Flexion 30°-60°	3.1	1.27	3.3	1.00	0.86	0.54	0.96	0.44	1.23
Flexion 60°-90°	3.2	1.40	3.3	1.35	0.92	0.72	0.98	0.40	1.10
Non-dominant Leg								
Extension 10°-30°	2.9	1.45	2.8	1.84	0.73	0.22	0.93	0.88	2.45
Extension 30°-60°	2.4	1.27	2.4	1.34	0.87	0.55	0.97	0.50	1.38
Extension 60°-90°	1.9	0.82	2.0	1.27	0.76	0.31	0.76	0.53	1.47
Flexion 10°-30°	2.2	0.64	2.2	1.04	0.65	0.05	0.90	0.52	1.45
Flexion 30°-60°	4.0	1.80	3.6	1.54	0.79	0.38	0.94	0.75	2.09
Flexion 60°-90°	3.8	1.89	3.5	2.08	0.84	0.50	0.96	0.80	2.23

[1]Session One Data; [2]Session Two Data

Table 2. Mean (°), standard deviation (SD), 95% confidence intervals (CI), standard error of measurement (SEM), smallest detectable difference (SDD) and intraclass correlation coefficient (ICC) values in a prone condition.

Relative Error Scores (RES)									
Test	Mean[1]	SD[1]	Mean[2]	SD[2]	ICC	95% CI		SEM	SDD
Dominant Leg									
Extension 10°-30°	2.0	2.16	2.5	2.96	0.75	0.26	0.93	1.31	3.62
Extension 30°-60°	0.9	3.19	1.4	2.07	0.54	-0.09	0.86	1.82	5.05
Extension 60°-90°	0.4	1.55	0.6	1.69	0.53	-0.10	0.86	1.11	3.08
Flexion 10°-30°	-0.7	1.34	-1.2	1.34	0.67	0.12	0.91	0.77	2.13
Flexion 30°-60°	-2.6	3.74	-2.3	3.03	0.69	0.15	0.91	1.90	5.28
Flexion 60°-90°	-1.6	1.74	-2.3	1.67	0.68	0.12	0.91	0.97	2.69
Non-dominant Leg									
Extension 10°-30°	2.1	2.7	1.3	2.45	0.74	0.24	0.93	1.33	3.68
Extension 30°-60°	1.4	2.61	0.6	2.04	0.61	0.02	0.89	1.45	4.03
Extension 60°-90°	-0.2	1.51	-0.4	1.94	0.74	0.24	0.93	0.89	2.48
Flexion 10°-30°	-1.5	1.50	-2.0	2.15	0.79	0.35	0.94	0.85	2.37
Flexion 30°-60°	-2.4	4.20	-1.7	5.61	0.60	-0.01	0.88	3.14	8.71
Flexion 60°-90°	-2.1	3.08	-1.8	3.03	0.58	-0.04	0.88	1.98	5.50
Absolute Error Scores (AES)									
Test	Mean[1]	SD[1]	Mean[2]	SD[2]	ICC	95% CI		SEM	SDD
Dominant Leg									
Extension 10°-30°	3.0	1.54	4.1	1.86	0.75	0.27	0.93	0.86	2.37
Extension 30°-60°	3.4	2.10	3.5	1.56	0.74	0.26	0.93	0.94	2.60

Extension 60°-90°	2.0	0.83	2.0	0.86	0.44	-0.23	0.82	0.64	1.76
Flexion 10°-30°	1.9	0.84	2.1	1.71	0.27	-0.40	0.75	1.15	3.20
Flexion 30°-60°	5.0	2.35	4.5	2.03	0.87	0.56	0.97	0.79	2.19
Flexion 60°-90°	3.7	1.53	3.8	1.38	0.61	0.01	0.89	0.91	2.53
Non-dominant Leg									
Extension 10°-30°	4.0	1.85	3.0	1.57	0.67	0.11	0.91	0.99	2.75
Extension 30°-60°	3.9	1.88	3.2	1.65	0.82	0.42	0.95	0.76	2.10
Extension 60°-90°	2.2	1.39	2.3	1.37	0.71	0.19	0.92	0.75	2.07
Flexion 10°-30°	2.7	1.64	2.9	1.91	0.85	0.51	0.96	0.69	1.90
Flexion 30°-60°	5.1	2.52	6.0	4.23	0.25	-0.42	0.74	3.02	8.37
Flexion 60°-90°	5.2	2.02	4.7	1.77	0.90	0.66	0.98	0.59	1.65

[1]Session One Data; [2]Session Two Data

Table 3. Mean (°), standard deviation (SD), 95% confidence intervals (CI), standard error of measurement (SEM), smallest detectable difference (SDD) and intraclass correlation coefficient (ICC) values in an active condition.

Test	Mean[1]	SD[1]	Mean[2]	SD[2]	ICC	95% CI		SEM	SDD
Relative Error Scores (RES)									
Dominant Leg									
Extension 10°-30°	0.8	0.59	0.5	1.16	-0.18	-0.71	0.47	1.00	2.78
Extension 30°-60°	1.5	1.59	1.1	2.13	0.49	-0.16	0.84	1.34	3.71
Extension 60°-90°	0.2	2.30	-0.1	2.16	0.24	-0.42	0.74	1.94	5.39
Flexion 10°-30°	-1.4	1.97	-0.8	1.57	0.33	-0.34	0.78	1.46	4.04
Flexion 30°-60°	-1.4	1.60	-1.3	1.77	0.36	-0.31	0.79	1.35	3.74
Flexion 60°-90°	-0.7	0.92	0.1	0.89	0.14	-0.50	0.69	0.84	2.32
Non-dominant Leg									
Extension 10°-30°	0.9	1.03	0.4	0.80	0.89	0.62	0.97	0.30	0.85
Extension 30°-60°	1.1	1.67	1.8	2.11	0.26	-0.40	0.75	1.64	4.54
Extension 60°-90°	0.6	1.62	0.4	1.19	0.03	-0.59	0.62	1.40	3.89
Flexion 10°-30°	-1.9	1.51	-1.6	1.84	0.37	-0.30	0.80	1.33	0.85
Flexion 30°-60°	-1.5	1.29	-1.2	1.51	0.37	-0.30	0.80	1.11	4.54
Flexion 60°-90°	-0.8	0.83	-0.5	1.30	0.51	-0.13	0.85	0.76	3.89
Absolute Error Scores (AES)									

Test	Mean[1]	SD[1]	Mean[2]	SD[2]	ICC	95% CI		SEM	SDD
Dominant Leg									
Extension 10°-30°	1.8	0.52	1.6	0.49	-0.13	-0.68	0.51	0.54	1.49
Extension 30°-60°	3.0	1.49	3.0	1.02	0.41	-0.25	0.81	0.98	2.72
Extension 60°-90°	3.8	1.01	3.3	0.89	0.06	-0.56	0.64	0.92	2.56
Flexion 10°-30°	3.2	1.27	2.3	0.84	0.42	-0.25	0.81	0.82	2.28
Flexion 30°-60°	2.5	1.01	2.6	1.24	0.00	-0.60	0.60	1.13	3.14
Flexion 60°-90°	1.7	0.58	1.8	0.62	-0.20	-0.72	0.46	0.66	1.83
Non-dominant Leg									
Extension 10°-30°	1.7	0.79	1.5	0.72	0.66	0.09	0.90	0.44	1.23
Extension 30°-60°	2.9	1.23	3.0	1.00	0.67	0.11	0.91	0.64	1.78
Extension 60°-90°	3.5	1.15	3.0	0.88	0.54	-0.09	0.86	0.69	1.92
Flexion 10°-30°	2.8	1.05	3.0	1.15	0.82	0.42	0.95	0.47	1.31
Flexion 30°-60°	2.7	0.52	3.0	1.10	0.22	-0.44	0.72	0.76	2.11
Flexion 60°-90°	1.7	0.51	1.9	0.84	0.17	-0.48	0.70	0.63	1.76

[1]Session One Data; [2]Session Two Data

Appendix 1e: Criterion-related validity of knee joint position sense measurement using image capture and isokinetic dynamometry.

Criterion-Related Validity of Knee Joint-Position-Sense Measurement Using Image Capture and Isokinetic Dynamometry

Nicola Relph and Lee Herrington

Context: Clinicians require portable, valid, and cost-effective methods to monitor knee joint-position-sense (JPS) ability. **Objective:** To examine the criterion-related validity of image-capture JPS measures against an isokinetic-dynamometer (IKD) procedure. **Design:** Random crossover design providing a comparison of knee JPS measures from image capture and IKD procedures. **Participants:** 10 healthy participants, 5 female, age 28.0 ± 13.29 y, mass 60.3 ± 9.02 kg, height 1.65 ± 0.07 m, and 5 male, 29.6 ± 10.74 y, mass 73.6 ± 5.86 kg, height 1.75 ± 0.07 m. **Main Outcome Measures:** The dependent variables were absolute error scores (AES) provided by 2 knee directions (flexion and extension). The independent variables were the method (image capture and IKD). **Results:** There was no significant difference between clinical and IKD AES into knee-flexion data ($P = .263$, $r = 0.55$). There was a significant difference between clinical and IKD AES into knee-extension data ($P = .016$, $r = .70$). **Conclusions:** Analysis of photographic images to assess JPS measurements using knee flexion is valid against an IKD positioning method, but JPS measurements using knee extension may not be valid against IKD techniques. However, photo-analysis measurements provided a lower error score using knee-extension data and thus may provide an optimal environment to produce maximal knee JPS acuity. Therefore, clinicians do not need expensive equipment to collect representative JPS ability.

Keywords: proprioception, isokinetic dynamometer, knee extension, knee flextion

Clinicians use knee joint-position-sense (JPS) measurements to assess static knee proprioception ability.[1] This is an important measurement, as it can either identify patients with a JPS deficiency that may lead to an increased risk of knee injury or progress along a proprioceptive-based rehabilitation program. The traditional clinical JPS measurement technique involves passive knee movement by the clinician to a specific target angle, then active reproduction of this angle by the patient.[1] Image capture can be used to collect knee position and hence knee JPS information. However, as the clinician is part of this data-collection process, measurement bias[2] may be introduced to the data. Therefore, an isokinetic dynamometer (IKD) provides an alternate means to position the knee target angle, removing researcher bias. Kiran et al[3] reported high correlations between concurrent measurement of JPS using an IKD, photo analysis, and electrogoniometry. However, all target knee positions were completed by the IKD arm and therefore did not replicate a typical clinical setting. Grob et al[4] did consider the correlation between a self-built low-speed motor and

passive researcher positioning techniques on different occasions. Results indicated a poor correlation between the 2 measurements ($r = -.2$), suggesting that the methods should not be used interchangeably. It is notable that when the target angle was positioned by the researcher rather than a pulley system, participants produced better JPS acuity results. However, the matching method was produced using a visual analog scale, which has limited ecological validity.[1]

Smith et al[5] produced a systematic review on the reliability of JPS measurement techniques. Their findings suggested that intrarater reliability depended on data-acquisition techniques; image capture produced greater reliability than electrogoniometry and dynamometry. However, no study has considered the concurrent validity of assessment methods using the same participants.[5] An analysis of the validity of JPS techniques is difficult, as there is no universally accepted "gold standard" method of collecting JPS data. However, the use of an IKD to position a limb at a defined angle is accepted. Therefore, criterion-related, specifically concurrent validity was investigated in this study by comparing a clinical JPS measurement technique with an IKD JPS protocol. Concurrent validity is defined as a comparison between 1 previously validated protocol and a new or previously unvalidated procedure.[6] Clinicians use JPS to measure the effectiveness of a rehabilitation

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program, so it is imperative that the measurements have concurrent validity. The aim of the current study was to validate measurement of JPS using a clinical researcher passive-positioning technique versus an IKD-positioning technique.

Methods

A convenience sample of 10 healthy participants took part in the study (see Table 1 and Appendix). All were free from lower-extremity injury and neurological disease and had no previous history of significant knee injury or surgery. Participants read an information sheet and provided written informed consent. This study was approved by the university ethics board. The dependent variables were collected using IKD (Humac Norm 776, CSMi, Stoughton, MA, USA) and image-capture procedures. The image-capture equipment included a camera (Casio Exilim, EX-FC100, Casio Electronics Co, Ltd, London, UK) and a tripod (Camlink TP-2800, Camlink UK, Leicester, UK). The camera setup followed the British Association of Sport and Exercise Sciences (BASES) guidelines.[7]

Procedures

The study was a random crossover design; hence, participants were tested using both methods, a week apart. Participants wore shorts and removed the sock and shoe from their dominant-leg foot. The participants were prepared for image-capture data collection by placing markers on the following anatomical points: a point on a line following the greater trochanter to the lateral epicondyle, close to the lateral epicondyle (placement of a marker directly on the greater trochanter is difficult due to clothing), the lateral epicondyle, and the lateral malleolus of the dominant leg (following Andersen et al[8]).

Each participant was seated on the end of an orthopedic assessment plinth and blindfolded (see Figure 1). The dominant leg was passively moved by the researcher through 30° to 60° of knee extension from a starting knee angle of 90° or through 60° to 90° of knee flexion from a starting angle of 0° to a target angle at an angular velocity of approximately 10°/s. The order of the target angles was randomly allocated using randomly generated numbers. The participant then actively held the leg

in this position for 5 seconds. A photograph of the leg in the target position was taken using the camera placed 3 m from the sagittal plane of movement on the fixed-level tripod. The leg was then passively returned to the starting angle, and the participant was instructed to actively move that leg to the target angle and hold it in this position. Another photograph was taken, and the participant instructed to move the leg back to the starting position. The process was repeated 5 times for each target angle on the dominant leg.

Knee JPS measurements were also collected using an IKD. A specific protocol was written (see Table 2) to ensure that the IKD passively moved the participant's dominant leg to the predetermined target angles. The participant was seated in the IKD chair but not secured in the chair, as this may have introduced sensory feedback from the popliteal fossa, which was not present in the clinical trials. Once the center of rotation of the dominant knee had been correctly aligned to the center of rotation of the IKD lever axis, the leg was strapped to the lever and the participant blindfolded. The IKD protocol then passively moved the leg through 30° to 60° of extension from a starting knee angle of 90° or through 60° to 90°
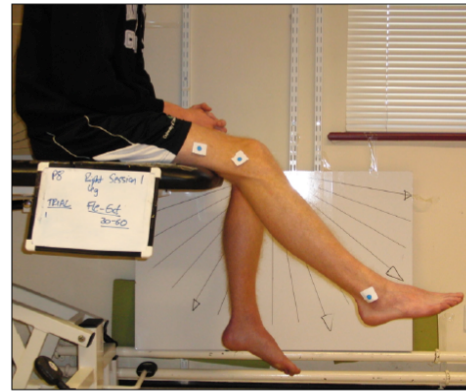
Figure 1 — Typical setup for image-capture knee-joint position-sense measurements.

Table 1   Participant Characteristics (Mean ± SD)

	Age (y)	Mass (kg)	Height (m)	BMI	GPPAQ range	KOOS	Lysholm	Tegner
Females (n = 5)	28.0 ± 13.29	60.3 ± 9.02	1.65 ± 0.07	22.1 ± 1.80	Inactive to active	98.6 ± 3.18	98.8 ± 2.68	5.0 ± 1.22
Males (n = 5)	29.6 ± 10.74	73.6 ± 5.86	1.75 ± 0.07	24.1 ± 1.97	Active	92.5 ± 10.87	87.6 ± 17.5	7.8 ± 1.30

Abbreviations: BMI, body-mass index; GPPAQ, General Practitioner Physical Activity Questionnaire; KOOS, Knee injury and Osteoarthritis Outcome Score (the closer the score to 100, the better the knee condition); Lysholm, Lysholm Knee Score (the closer the score to 100, the better the knee condition); Tegner, Tegner Activity Scale (the closer the score to 10, the more physically active) (see Appendix for more details).

Table 2   Isokinetic Dynamometer Protocol

Action	Angle (°)	Hold time (s)
From 0° (full extension) into knee flexion		
passive	90/80/70/90/75	5
passive	0	2
active	Replication	5
passive	0	Back to step 1
From 90° into knee extension (0°)		
passive	30/45/60/45/45	5
passive	90	2
active	Replication	5
passive	90	Back to step 1

Note: Passive action defines isokinetic dynamometer lever movement. Active motion defines participant muscle contraction.

of flexion from a starting angle of 0° to a specified target angle at an angular velocity of 2°/s. Target angles were randomly selected across the range of motion. The leg was held in this position for 5 seconds and then returned to the starting angle. The participant was then instructed to move the leg to the target angle and hold, at which point the experimenter noted the knee angle using the IKD software. This process was repeated 5 times for both knee extension and flexion.

Data Reduction

Knee angles were measured from the image-capture data using 2-dimensional manual digitizing software (ImageJ, US National Institutes of Health, Bethesda, MD, USA, http://imagej.nih.gov/ij/, 1997). Knee JPS was calculated from the average delta scores between target and reproduction angles across 5 flexion and 5 extension trials, producing absolute error scores (AES) in which only magnitude was measured. Interexaminer and intraexaminer reliability were confirmed using intraclass correlation coefficients (ICC 2,1).[9] The ICC value corresponding to interexaminer reliability was .98, and 95% confidence intervals ranged from .96 to .99. The ICC value for intraexaminer reliability was .96, and 95% confidence intervals ranged from .91 to .98. Therefore it can be confirmed that interreliability and intrareliability of the data-analysis method were at an acceptable level. Test–retest reliability was confirmed before the current study; knee-extension trials provided an ICC of .89 and knee-flexion trials an ICC of .92.

AES scores from IKD data were calculated by subtracting the reproduction angle from the target angle set in the protocol. The averages of the 5 extension trials and 5 flexion trials were used for further analysis in each condition (photo analysis and IKD).

All statistical analysis was completed in SPSS (Version 19, IBM Corp, Armonk, NY, USA). The Shapiro-Wilk test was used to examine normality of data, which was confirmed. Related-samples t tests were used to compare clinical and IKD JPS scores. An alpha level was set at $P < .05$. The corresponding t statistic and degrees of freedom were used to calculate effect size (r).[9]

Results

There was no significant difference between image-capture AES (3.7° ± 1.4°) and IKD AES (4.3° ± 1.8°) knee-flexion data ($P = .263$, $r = .55$). There was a significant difference between image-capture AES (2.5° ± 0.7°) and IKD AES (4.3° ± 1.9°) knee-extension data ($P = .016$, $r = .70$).

Discussion

Clinicians use JPS to measure the effectiveness of a rehabilitation program and identify patients who may be more at risk for knee injury, so it is imperative that the measurements be valid. Criterion-related validity was confirmed for knee-flexion JPS; there were no differences between JPS in a clinical and IKD setting ($P = .263$, $r = .55$). However, knee-extension JPS using an image-capture technique was different than an IKD-based technique ($P = .016$, $r = .70$). The IKD data provided significantly greater error scores than the image-capture data for knee extension. This supports previous evidence that JPS measurement techniques should not be used interchangeably; however, passive positioning by a researcher may provide a more optimal environment for maximal JPS performance.[4] It is possible in the IKD setting that participants had to adapt to the addition of the lever arm increasing the mass of the leg and the torque required to extend the knee; hence, effort was not as natural when compared with the image-capture setting and ecological validity was reduced. This may not have the same effect on knee flexion, as the torque required in this direction would be assisted by gravity. Another feasible explanation was the seating in both tests. In the image-capture test condition participants were seated on the edge of a

plinth and hence were not conscious of a back rest and could use pelvis rotation to assist knee extension and the associated hamstring lengthening. Previous research suggests heightened afferent information when muscles are lengthened.[10] In the IKD setting participants were seated on the edge of the seat and not supported by the back rest but may have been less likely to use pelvis rotation to assist knee extension and hence perhaps use a less natural (more resistance to) knee-extension movement. Therefore, a clinical setting may provide a more "optimal" environment for knee-extension JPS measurement, as ecological validity is increased.

Results of this validity study have important implications for clinicians. The image-capture measurement of knee JPS with passive positioning of target angles produced similar (knee flexion) and improved (knee extension) AES compared with the IKD setting. This suggests that a clinical measurement technique provides a more optimal environment and "best scores" for JPS than an IKD setting. Therefore, knee JPS can be measured in a clinical setting using cheap and easily accessible equipment; expensive IKD equipment is not necessary.

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Appendix: Questionnaires Used to Define Participants' Knee-Function Score (KOOS and Lysholm) and Activity Level (GPPAQ and Tegner)

NHS

General Practice Physical Activity Questionnaire

Date...........................

Name.........................

1. Please tell us the type and amount of physical activity involved in your work.

		Please mark one box only
a	I am not in employment (e.g. retired, retired for health reasons, unemployed, full-time carer etc.)	
b	I spend most of my time at work sitting (such as in an office)	
c	I spend most of my time at work standing or walking. However, my work does not require much intense physical effort (e.g. shop assistant, hairdresser, security guard, childminder, etc.)	
d	My work involves definite physical effort including handling of heavy objects and use of tools (e.g. plumber, electrician, carpenter, cleaner, hospital nurse, gardener, postal delivery workers etc.)	
e	My work involves vigorous physical activity including handling of very heavy objects (e.g. scaffolder, construction worker, refuse collector, etc.)	

2. During the *last week*, how many hours did you spend on each of the following activities? *Please answer whether you are in employment or not*

		Please mark one box only on each row			
		None	Some but less than 1 hour	1 hour but less than 3 hours	3 hours or more
a	Physical exercise such as swimming, jogging, aerobics, football, tennis, gym workout etc.				
b	Cycling, including cycling to work and during leisure time				
c	Walking, including walking to work, shopping, for pleasure etc.				
d	Housework/Childcare				
e	Gardening/DIY				

3. How would you describe your usual walking pace? Please mark one box only.

Slow pace (i.e. less than 3 mph)		Steady average pace	
Brisk pace		Fast pace (i.e. over 4mph)	

Appendix Figure 1 — GPPAQ. Credit to the Department of Health, England.

Knee injury and Osteoarthritis Outcome Score (KOOS), English version LK1.0

KOOS KNEE SURVEY

Today's date: _____/_____/_____   Date of birth: _____/_____/_____

Name: _____

INSTRUCTIONS: This survey asks for your view about your knee. This information will help us keep track of how you feel about your knee and how well you are able to perform your usual activities.

Answer every question by ticking the appropriate box, only <u>one</u> box for each question. If you are unsure about how to answer a question, please give the best answer you can.

Symptoms
These questions should be answered thinking of your knee symptoms during the **last week**.

S1. Do you have swelling in your knee?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S2. Do you feel grinding, hear clicking or any other type of noise when your knee moves?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S3. Does your knee catch or hang up when moving?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S4. Can you straighten your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

S5. Can you bend your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

Stiffness
The following questions concern the amount of joint stiffness you have experienced during the **last week** in your knee. Stiffness is a sensation of restriction or slowness in the ease with which you move your knee joint.

S6. How severe is your knee joint stiffness after first wakening in the morning?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

S7. How severe is your knee stiffness after sitting, lying or resting **later in the day**?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Appendix Figure 2(a) — Knee Injury and Osteoarthritis Outcome Scale (KOOS), part 1.

Knee injury and Osteoarthritis Outcome Score (KOOS), English version LK1.0

Pain

P1. How often do you experience knee pain?

Never	Monthly	Weekly	Daily	Always
▫	▫	▫	▫	▫

What amount of knee pain have you experienced the **last week** during the following activities?

P2. Twisting/pivoting on your knee

None	Mild	Moderate	Severe	Extreme
▫	▫	▫	▫	▫

P3. Straightening knee fully

None	Mild	Moderate	Severe	Extreme
▫	▫	▫	▫	▫

P4. Bending knee fully

None	Mild	Moderate	Severe	Extreme
▫	▫	▫	▫	▫

P5. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
▫	▫	▫	▫	▫

P6. Going up or down stairs

None	Mild	Moderate	Severe	Extreme
▫	▫	▫	▫	▫

P7. At night while in bed

None	Mild	Moderate	Severe	Extreme
▫	▫	▫	▫	▫

P8. Sitting or lying

None	Mild	Moderate	Severe	Extreme
▫	▫	▫	▫	▫

P9. Standing upright

None	Mild	Moderate	Severe	Extreme
▫	▫	▫	▫	▫

Function, daily living

The following questions concern your physical function. By this we mean your ability to move around and to look after yourself. For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A1. Descending stairs

None	Mild	Moderate	Severe	Extreme
▫	▫	▫	▫	▫

A2. Ascending stairs

None	Mild	Moderate	Severe	Extreme
▫	▫	▫	▫	▫

Appendix Figure 2(b) — Knee Injury and Osteoarthritis Outcome Scale (KOOS), part 2.

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For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A3. Rising from sitting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A4. Standing

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A5. Bending to floor/pick up an object

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A6. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A7. Getting in/out of car

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A8. Going shopping

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A9. Putting on socks/stockings

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A10. Rising from bed

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A11. Taking off socks/stockings

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A12. Lying in bed (turning over, maintaining knee position)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A13. Getting in/out of bath

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A14. Sitting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A15. Getting on/off toilet

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Appendix Figure 2(c) — Knee Injury and Osteoarthritis Outcome Scale (KOOS), part 3.

Knee injury and Osteoarthritis Outcome Score (KOOS), English version LK1.0

For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A16. Heavy domestic duties (moving heavy boxes, scrubbing floors, etc)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A17. Light domestic duties (cooking, dusting, etc)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Function, sports and recreational activities
The following questions concern your physical function when being active on a higher level. The questions should be answered thinking of what degree of difficulty you have experienced during the **last week** due to your knee.

SP1. Squatting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP2. Running

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP3. Jumping

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP4. Twisting/pivoting on your injured knee

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP5. Kneeling

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Quality of Life

Q1. How often are you aware of your knee problem?

Never	Monthly	Weekly	Daily	Constantly
☐	☐	☐	☐	☐

Q2. Have you modified your life style to avoid potentially damaging activities to your knee?

Not at all	Mildly	Moderately	Severely	Totally
☐	☐	☐	☐	☐

Q3. How much are you troubled with lack of confidence in your knee?

Not at all	Mildly	Moderately	Severely	Extremely
☐	☐	☐	☐	☐

Q4. In general, how much difficulty do you have with your knee?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Thank you very much for completing all the questions in this questionnaire.

Appendix Figure 2(d) — Knee Injury and Osteoarthritis Outcome Scale (KOOS), part 4.

Lysholm Knee Questionnaire / Tegner Activity Scale

Name: [   ] [   ]   **Date:** 09 01 14

First   Last

Physician: [   ]

1. Limp:
- ○ a) None
- ○ b) Slight or periodical
- ○ c) Severe and constant

2. Support:
- ○ a) None
- ○ b) Stick or crutch
- ○ c) Weight-bearing impossible

3. Locking:
- ○ a) No locking and no catching sensations
- ○ b) Catching sensation but no locking
- ○ c) Locking occasionally
- ○ d) Locking frequently
- ○ e) Locked joint on examination

4. Instability:
- ○ a) Never giving way
- ○ b) Rarely during athletics or other severe exertion
- ○ c) Frequently during athletics or other severe exertion (or incapable of participation)
- ○ d) Occasionally in daily activities
- ○ e) Often in daily activities
- ○ f) Every step

5. Pain:
- ○ a) None
- ○ b) Inconstant and slight during severe exertion
- ○ c) Marked during severe exertion
- ○ d) Marked on or after walking more than 2 km
- ○ e) Marked on or after walking less than 2 km
- ○ f) Constant

6. Swelling:
- ○ a) None
- ○ b) On severe exertion
- ○ c) On ordinary exertion
- ○ d) Constant

7. Stair-climbing:
- ○ a) No problems
- ○ b) Slightly impaired
- ○ c) One step at a time
- ○ d) Impossible

8. Squatting:
- ○ a) No problems
- ○ b) Slightly impaired
- ○ c) Not beyond 90°
- ○ d) Impossible

Appendix Figure 3(a) — Lysholm/Tegner Scales, part 1.

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Activity Level Before Injury	Current Activity Level	Activity Level Following Surgery if applicable	
○	○	○	Competitive sports Soccer - national and international elite

○	○	○	Competitive sports
			    Soccer, lower divisions
			    Ice hockey
			    Wrestling
			    Gymnastics

○	○	○	Competitive sports
			    Bandy
			    Squash or badminton
			    Athletics (jumping, etc.)
			    Downhill skiing

○	○	○	Competitive sports
			    Tennis
			    Athletics (running)
			    Motorcross, speedway
			    Handball
			    Basketball
			Recreational sports
			    Soccer
			    Bandy and ice hockey
			    Squash
			    Athletics (jumping)
			    Cross-country track findings both recreational and competitive

○	○	○	Recreational sports
			    Tennis and badminton
			    Handball
			    Basketball
			    Downhill skiing
			    Jogging, at least five times per week

○	○	○	Work Heavy labor (e.g., building, forestry)
			Competitive sports
			    Cycling
			    Cross-country skiing
			Recreational sports
			    Jogging on uneven ground at least twice weekly

○	○	○	Work Moderately heavy labor (e.g., truck driving, heavy domestic work)
			Recreational sports
			    Cycling
			    Cross-country skiing
			    Jogging on even ground at least twice weekly

○	○	○	Work Light labor (e.g., nursing) Competitive and recreational sports Swimming Walking in forest possible
○	○	○	Work Light labor Walking on uneven ground possible but impossible to walk in forest
○	○	○	Work Sedentary work Walking on even ground possible
○	○	○	Sick leave or disability pension because of knee problems

Tegner: [ ]   [ ]   [ ]   Lysholm Score: [0]   [Print Form]   [Submit]

Appendix Figure 3(b) — Lysholm/Tegner Scales, part 2.

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Appendix 1f: Relph, N., & Herrington, L. (2015). The Effect of Peripheral Fatigue on Knee Joint Position Sense. Paper presented at the *International Society of Biomechanics Conference*, Glasgow, UK.

ISB 2015

Injury

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THE EFFECT OF PERIPHERAL FATIGUE ON KNEE JOINT POSITION SENSE.

N S Relph[*][1], L C Herrington[2]

[1]University of Cumbria, Carlisle, [2]University of Salford, Salford, United Kingdom

Preferred Presentation: Poster Presentation

Clinical Biomechanics Award: Yes

David Winter Young Investigator Awards: Yes

David Winter Award - presentation Preference: Poster

Emerging Scientific Award sponsored by Professor J De Luca: No

Promising Scientist Award sponsored by Motion Analysis: No

Introduction and Objectives: Muscular fatigue is the inability to maintain a power output or force during repeated muscular contractions due to changes in physiological processes. Joint position sense (JPS) is the awareness of position in space. Exercising when fatigued increases the risk of injury, which may be due to a reduction in knee position sense. Indeed, evidence suggests more injuries occur in the final third of sports matches than in earlier periods. The aim of this study was to measure the effect of peripheral muscular fatigue on knee JPS.

Methods: 20 healthy participants provided informed consent. Knee JPS was recorded before and after a fatiguing protocol. The JPS measurements were taken using a previously validated method (Relph and Herrington, 2014a, 2014b). This involved open chain, passive-active reproduction of a target angle into both flexion and extension. Absolute error scores (AES) were taken as the absolute difference between target and reproduction angles. Angles were measured using image capture and manual digitising techniques. Fatiguing protocol was conducted on an isokinetic dynamometer and involved concentrically extensions and flexions of the dominant knee maximally at 60°/s until they reached 50% of their maximum voluntary contraction on three consecutive trials in both flexor and extensor muscle groups.

Results: The mean (±SD) maximum voluntary contraction into knee flexion and extension was 78.7N.m (±22.8) and 177.1N.m (±39.0) respectively. Results of the analysis revealed no effect of the fatiguing protocol on either JPS flexion (p=0.729) or JPS extension (p=0.492). Knee JPS flexion error scores reduced by 0.17° and JPS extension error scores reduced by 0.14°. Discussion - One viable explanation of the results of this study is the fatiguing protocol was not severe enough to induce a fatigued state. For example the anterior shear loads imposed on the knee joint during isokinetic contraction at 180°/s are equivocal to that of walking and compressive loads equivalent to stair climbing. This suggests studies using isokinetic fatiguing may not create representative fatiguing of the joint as would occur during exercise. The method of measuring fatigue levels using 50% of MVC may also have limitations. It may be more appropriate to use blood analysis techniques to confirm fatigue. However, it would appear peripheral fatigue occurred to some extent as MVC performance did reduce. Another explanation for the lack of JPS decline may be compensatory techniques in the central nervous system, central processing may have adjusted efferent information to ensure continued to provide accurate joint position sense.

Conclusion: In conclusion, peripheral fatiguing protocols may not induce fatigue to an appropriate level to illustrate the effects on knee JPS. Alternatively, knee JPS may not be affected by fatigue and hence a reduction in knee static proprioception may not be a mechanism of the increased risk of injury during the latter stage of exercise and sport. Future research should consider the effect of central fatiguing on knee proprioception. Disclosure -This data is new and has not been submitted elsewhere.

References: Reference 1

Relph et al. (2014a). Inter-Examiner, Intra-Examiner and Test-Retest Reliability of Clinical Knee Joint Position Sense Measurements Using an Image Capture Technique. J. Sport Rehabil., In Press.

Appendix 2: Participant Information Sheet for Clinical JPS Testing

Information To Participate In A Research Project

You are invited to take part in a research study which could provide important information for the measurement of knee position sense.

What is the project all about?

The study is looking at knee joint position sense in uninjured participants, as this may be linked to predicting knee injury risk in athletes.

What will I have to do?

You will be required to participate in a knee joint angle measurement task that requires you to move your knee to a predetermined angle, set by the researcher, in a controlled laboratory environment at the University of Salford. The testing will not involve any exertion that you are not accustomed with through your current activity levels and will be conducted in sessions lasting 30mins maximum.

Is there any risk involved?

There is an inherent risk with any type of testing, however the testing for this study will be in a controlled laboratory environment and therefore any risks are minimal.

Who will see my details and results?

A photograph of your leg only will be taken. All personal information will be kept strictly confidential. The final results of the study will be available to you, and may be published.

You are free to decide not to be in this trial or to drop out at any time.

Please feel free to ask any further questions about the nature or demands of the project at any time.

Many thanks for your participation.

Nicola Relph

Appendix 3: Participant Informed Consent Form for Clinical JPS Testing

Participant Informed Consent Form

1. *Nicola Relph,* who is a Postgraduate research student at the University of Salford, has requested my participation in a research study. My involvement in the study and its purpose has been fully explained to me.

2. My participation in this research will involve trials that involve movement of the knee joint to set target angles.

3. I have been informed that this research does not involve any additional risk that does not occur normally during everyday activity.

4. I understand the requirements of the study and my involvement and the possible benefit of my participation in this research

5. I have been informed that I will not be compensated for my participation.

6. I understand that the results of this research may be published but that my name or identity will not be revealed at any time. In order to keep my records confidential, *Nicola Relph* will store all information as numbered codes in computer files that will only be available to her.

7. I have been informed that any questions I have at any time concerning the research or my participation in it, will be answered by Nicola Relph and I can contact her at: Nicola.Relph@Cumbria.ac.uk

8. I have read the above information. I understand the nature, demands, risks and benefits of the project and I agree to participate in this research. However, I understand that I may withdraw my consent and participation at any time without objection from the researcher.

Signed: **Date:**

Name:

Witnessed: **Date:**

Appendix 4: Isokinetic Dynamometer Protocols

IKD Protocol from 0° into Flexion

Action	Angle (°)	Hold Time (s)
Passive	90/ 80/ 70/ 90/ 75	5
Passive	0	2
Active	Replication	5
Passive	0	Back to step 1

IKD Protocol from 90° into Extension

Action	Angle (°)	Hold Time (s)
Passive	30/ 45/ 60/ 45/ 45	5
Passive	90	2
Active	Replication	5
Passive	90	Back to step 1

Note. "Passive" action defines IKD lever movement. "Active" motion defines participant muscular contraction.

Appendix 5: Participant Information Sheet for Peripheral Fatigue Study

Information To Participate In A Research Project

You are invited to take part in a research study which could provide important information on the effects of fatigue on knee joint position sense, an aspect of knee proprioception.

What is the project all about?

The study is looking at knee joint position sense and fatigue in uninjured participants, as this may be linked to predicting knee injury risk in athletes. The test will be conducted on one occasion.

What will I have to do?

You will be required to participate in a knee joint angle measurement task that requires you to move your knee to a predetermined angle, set by the researcher, in a controlled laboratory environment at the University of Cumbria. A photograph of your knee will be taken at each set angle to measure your positioning. You will then be asked to extend and bend your knee joint at a set speed to measure you maximum strength performance and be asked to repeat this task until you are fatigued. The testing will be conducted in one session, taking no longer than 30 minutes.

Is there any risk involved?

There is an inherent risk with any type of testing, however the testing for this study will be in a controlled laboratory environment and therefore any risks are minimal. You will complete a sub-maximal warm up prior to data collection and the leg will be unloaded, lowering the risk of any injury.

Who will see my details and results?

All personal information will be kept strictly confidential. The final results of the study will be available to you, and may be published.

You are free to decide not to be in this trial or to drop out at any time. Please feel free to ask any further questions about the nature or demands of the project at any time.

Many thanks for your participation.

Nicola Relph

Appendix 6: Informed Consent Form for Peripheral Fatigue Study

Informed Consent Form

1. *Nicola Relph,* who is lecturer at the University of Cumbria, has requested my participation in a research study. My involvement in the study and its purpose has been fully explained to me.

2. My participation in this research will involve trials that involve movement of the knee joint to set target angles. A photograph of the knee will be taken at each set angle to measure positioning. My leg will then be fatigued. Then my knee position will be recorded again.

3. I have been informed that this research does not involve any additional risk that does not occur normally during everyday activity and exercise.

4. I understand the requirements of the study and my involvement and the possible benefit of my participation in this research.

5. I have been informed that I will not be compensated for my participation.

6. I understand that the results of this research may be published but that my name or identity will not be revealed at any time. In order to keep my records confidential, *Nicola Relph* will store all information as numbered codes in computer files that will only be available to her.

7. I have been informed that any questions I have at any time concerning the research or my participation in it, will be answered by Nicola Relph and I can contact her at:
   Nicola.Relph@Cumbria.ac.uk

8. I have read the above information. I understand the nature, demands, risks and benefits of the project and I agree to participate in this research. However, I understand that I may withdraw my consent and participation at any time without objection from the researcher.

Signed: **Date:**

Name:

Witnessed: **Date**

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