ACUITY OF FORCE APPRECIATION
IN THE OSTEOARTHRITIC KNEE JOINT

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ABBREVIATIONS

ADL	Activities of daily living
ANOVA	Analysis of variance
BMI	Body mass index
CHAMPS	Community Healthy Activities Model Program for Seniors physical activity questionnaire
CPAC	Clinical Priority Assessment Criteria
DRR	Detection response rate
EMG	Electromyography
g	gram
Hz	hertz
kg	kilogram
kph	kilometres per hour
lb	pound
L	Left
LLTQ	Lower Limb Task Questionnaire
MET	Metabolic equivalents
MRI	Magnetic resonance imaging
MVC	Maximal voluntary capacity
N	Newtons
Nm	Newton-meters
nMVC	Normative maximal voluntary capacity
OA	Osteoarthritis
p	Probability value (e.g. $p<0.05$)
PARQ	Physical Activity Readiness Questionnaire
r	Correlation coefficient (e.g. $r=0.137$)
R	Right
RS	Relative score
SD	Standard deviation
WOMAC	Western Ontario and McMaster Universities Osteoarthritis Index
$\bar{x}$	Mean

CERTIFICATE OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of a university or other institution of higher learning, except where due recognition is made in the acknowledgements.

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ABSTRACT

Osteoarthritis and ageing have been shown to induce changes in the number and health of peripheral mechanoreceptors. Whilst position and movement awareness in the osteoarthritic knee have been studied extensively, little work to date has been produced on muscle force awareness in this subject group. Poor force acuity may contribute to muscle and joint pain and dysfunction, and additionally hinder rehabilitation efforts in an osteoarthritic population. Overestimation of the muscles forces required for a given task, resulting in greater joint compression forces, may aggravate and inflame osteoarthritic symptoms. Underestimation of required muscle forces may amplify existing joint instability, increasing the risk of injury in an osteoarthritic population. Additionally, both under and overloading of muscles during the rehabilitation process can delay the return to full function after injury.

When regarding the neurological process of force coding, current debate centres on the relative importance of centrally generated motor command mediated 'sense of effort' versus the peripheral mechanoreceptor signalled 'sense of tension' as the dominant coding process, with central mechanisms favoured in the majority of studies published to date. The purpose of this study was to investigate muscle force awareness in the knee extensors and flexors and hands of subjects with and without knee joint osteoarthritis.

Twenty one subjects with knee joint osteoarthritis and 23 age and gender matched subjects with no known knee pathology were evaluated. All subjects performed ipsilateral isometric force estimation and force matching tasks, at levels scaled to individual maximum voluntary capacity (MVC). Errors in estimation and matching acuity were normalised to reference targets (comparison force/reference force) giving a relative score (RS) to allow comparison across submaximal force levels with RS less than 1.0 indicating that subjects produced insufficient force and vice versa.

Maximal voluntary capacity tests revealed significantly lower ($p<0.05$) peak knee extension torque (111.2 Nm versus 145.3 Nm), but similar peak knee flexion torque (46.1 Nm versus 45.4 Nm for osteoarthritis and control subjects

respectively). A pattern of overestimation at low reference levels and underestimation at high reference levels was demonstrated by all subjects. In the lower limb, force appreciation differed significantly between muscle groups regardless of knee condition, with knee extensors demonstrating greater overall accuracy than knee flexors. There was a significant difference ($p<0.05$) in force estimation ability and a trend to significance ($p=0.066$) for force matching acuity across groups at the 10% MVC test level. A significant ($p<0.05$) group difference in grip force estimation ability between the lowest and highest target levels was demonstrated.

It can be concluded that there are small differences in force acuity in osteoarthritis subjects at lower submaximal force targets when compared to healthy age matched peers. The notion of *information redundancy*, whereby no new proprioceptive inputs, regardless of origin, are able to effect an improvement in force acuity in a given situation has been demonstrated in previous studies that reported relatively stable force matching acuity at forces between 30% and 60% of maximal capacity. The poor comparative force perception demonstrated in this study by the osteoarthritis group at the lower submaximal test levels supports the notion that centrally generated copies of motor commands do not provide sufficient data to adequately encode force magnitude at low levels of force generation, evoking a greater reliance data received from peripheral mechanoreceptors. This has significant implications for this subject group given that the majority of daily tasks require only low levels of force generation. Given that perceptive acuity in a variety of sensory modalities has been shown to improve with training there may be a role for force perception training in older adults with osteoarthritis.

1. STATEMENT OF THE PROBLEM

1.1 Introduction

This study investigated force appreciation in the knee extensors, knee flexors and hands of subjects with and without osteoarthritis of the knee joint as measured using force estimation and force matching protocols.

Osteoarthritis is the cause of considerable pain and disability in older adults in New Zealand (New Zealand Ministry of Health, 2004). Nationally, almost 40% of men and over 50% of women aged over 65 years have been diagnosed with arthritis (New Zealand Ministry of Health, 2004) The precise aetiology of osteoarthritis remains unknown, but is thought to include both biochemical and biomechanical factors (Vad, Adin, & Solomon, 2004). Factors influencing the development of osteoarthritis include inherited predisposition, history of trauma, body composition/obesity, occupation or sports characterised by excessive and sustained joint loading, muscle weakness and neurological deficits (Felson & Neogi, 2004; Ikeda, Tsumura & Torisu, 2005; Slemenda et al., 1997; Steultjens, Dekker, van Baar, Oostendorp & Bijlsma, 2001; Vad et al., 2004). Symptoms experienced by sufferers of osteoarthritis include pain, instability or stiffness of the knee joint, muscle weakness, diminished balance, proprioceptive deficits, joint deformity and functional impairments (Koralewicz & Engh, 2000; McHugh, Luker, Campbell, Kay & Silman, 2007; Messier, Glasser, Ettinger, Craven & Miller, 2002; Szabo, Lovasz, Kustos, & Bener, 2000; Vad et al., 2004). Strength deficits have been demonstrated in the flexor and extensor muscles surrounding the arthritic knee (Fisher & Pendergast, 1994; Fisher, Kame, Rouse & Pendergast, 1994; Fransen, Crosbie & Edmonds, 2003; Goldman et al., 2003; Lin, Davey, & Cochrane, 2001; Madsen & Brot, 1996; Lewek, Rudolph, & Snyder-Mackler, 2004; Ordway, Hand, Briggs & Ploutz-Snyder, 2006; Silva et al., 2003) and pain in and of itself has been shown to cause considerable disruption to normal mechanoreceptor sensitivity (Felson, 2005; Grubb, 2004; Schaible & Grubb, 1993). Functional impairments include difficulty with walking , squatting, kneeling, getting in and out of chairs and the ascent and descent of stairs (Bennell et al., 2003; Gur & Cakin, 2003; Hurley, Scott, Rees & Newham, 1997).

The proprioceptive deficits that have been demonstrated in osteoarthritis sufferers include both delays in the detection of movement and poorer position matching ability (Koralewicz & Engh, 2000; Marsh, Rejeski, Lang, Miller & Messier, 2003). It has been demonstrated that middle aged and elderly individuals with osteoarthritis have bilateral deficits in the detection of passive movements which are not correlated with radiographically determined severity of degeneration at the knee joints (Koralewicz & Engh, 2000; Sharma, Pai, Holtkamp & Rymer, 1997). Subjects with unilateral osteoarthritis exhibit deficits in position-matching accuracy in both affected and unaffected limbs when performing loaded reposition tests (Garsden & Bullock-Saxton, 1999). In addition both static and dynamic standing balance are more impaired in older subjects with osteoarthritis than in age-matched controls (Hinman, Bennell, Metcalf & Crossley, 2002). As functional movement depends on good proprioceptive acuity (Gandevia, McCloskey, & Burke, 1992), these deficits will contribute to the deterioration in health-related quality of life seen in sufferers of osteoarthritis (Hurley et al., 1997).

A proprioceptive function less commonly considered is the ability to discern the forces generated by voluntary muscles (Gandevia et al., 1992). In the same way that kinaesthesia describes the perception of body position and movement, 'force appreciation' can be described as the awareness of forces generated during muscle contraction (Roland & Ladegaard-Pedersen, 1977). Synonyms include force-sensation, force-control, muscle-sense, motor-sense and force-awareness. As with kinaesthesia, many organs are proposed to encode force appreciation including Golgi tendon organs, muscle spindles, motor efferent firing patterns and corollary cortical discharges (Gandevia et al., 1992). Both input from cutaneous and joint receptors and visual feedback are thought to contribute to the acuity of force appreciation (Cafarelli, 1982; Carson, Riek, & Shahbazpour, 2002; Jones & Hunter, 1982).

Force appreciation is commonly measured by using magnitude estimation protocols, force and weight matching protocols or by studying the accuracy and precision of force production. Magnitude estimation studies reveal considerable variation in force acuity across subjects at different muscle forces; however subjects demonstrate high levels of consistency (Cafarelli & Bigland-Ritchie,

1979; Jackson & Dishman, 2000). That is, even if a subject's effort varies considerably from the target value, that subject will consistently reproduce an inaccurate result. Force matching protocols demonstrate that force is encoded relative to maximal capacity (Jones, 2003; McCloskey, Ebeling, & Goodwin, 1974; Williams, Hanson, Crary & Wharton, 1991). When asked to perform muscle contractions at 50% of MVC across limbs, forces produced will differ across limbs if maximal capacity differs for each limb, as subjects will produce efforts consistent with 50% of the individual limb's maximum. Matching studies have demonstrated that force appreciation is most accurate for target levels between 30–60% of maximum capacity and that individuals consistently overestimate small submaximal loads and underestimate loads that approach maximal capacity (Jones, 1989b; Westling & Johansson, 1984). Additionally, matching studies have shown that joint angle influences force acuity during matching tasks (Cafarelli & Bigland-Ritchie, 1979; Weerakkody, Percival, Morgan, Gregory & Proske, 2003b). Force generation studies assess force sense by measuring how accurately and precisely subjects can produce and maintain a reference force. Again accuracy and precision is best at levels in the midrange of an individual's force-generating capacity.

Disturbances in force appreciation have been demonstrated in the elderly, in the presence of pain, as a result of fatigue, after muscle damage, in the absence of visual feedback, when fatigued and as a result of strength training. The study of motor control during submaximal force production in older subjects has produced conflicting results. Schiffman, Luchies, Richards and Zebas (2002) demonstrated that elderly subjects tend to display greater accuracy and precision during sustained isometric force generation, although total forces produced are less. In force matching tasks, a significant disparity of matching acuity has been demonstrated in older subjects (Hortobágyi, Tunnel, Moody, Beam & DeVita, 2001). Tracy and Enoka (2002) also demonstrated reduced steadiness during submaximal isometric contractions but not eccentric or concentric contractions in older versus younger subjects. In the presence of pain, fatigue and or muscle damage, individuals have been shown to over-rate effort in the affected limb during force matching tasks such that subjects under exert affected muscles when matching healthy reference contractions (Cafarelli, 1988; Jones & Hunter, 1983; Proske et al., 2004; Weerakkody, Percival, Canny,

Morgan & Proske, 2003a; Weerakkody, et al., 2003b). Strength training has been demonstrated to improve force matching acuity in older subjects during performance of eccentric contractions (Hortobágyi et al., 2001).

Reduced force accuracy and precision during generation of submaximal forces has been demonstrated in subjects with osteoarthritis of the knee during isokinetic concentric and eccentric contractions of knee extensor muscles (Hortobágyi, Garry, Holbert & DeVita, 2004). Although no specific investigations of force matching acuity has been reported in subjects with osteoarthritis of the knee, the notion that these individuals may demonstrate impaired force appreciation is reasonable given that osteoarthritis of the knee is a condition commonly experienced by older adults and is characterised by increased pain, strength deficits, and deterioration in movement and position senses which result in balance impairments.

Poor force acuity may contribute to muscle and joint pain and dysfunction, and additionally hinder rehabilitation efforts in an osteoarthritic population. Overestimation of the muscle forces required for a given task, resulting in greater joint compression forces, may aggravate and inflame osteoarthritic symptoms. Underestimation of required muscle forces may amplify existing joint instability, increasing the risk of injury in an osteoarthritic population. Additionally, both under and overloading of muscles during the rehabilitation process can delay the return to full function after injury.

1.2 PURPOSE STATEMENT

The purpose of the study was to investigate force appreciation in the knee extensor and knee flexor muscle groups of healthy adults with unilateral osteoarthritis of the knee and compare the findings to an age and gender matched group who were without pathology. Testing was conducted at submaximal force levels (10%, 25%, 50% and 75% MVC) and the primary variable of interest was relative error (matching torque divided by target torque).

1.3 SIGNIFICANCE OF THE STUDY

Although rehabilitation specialists have adopted an array of tests and techniques to assess balance and movement awareness, the ability to perceive and accurately reproduce specific muscle forces has not been well investigated in people with osteoarthritis. In seeking to assess the force estimation and force matching ability of older adults with and without knee joint degeneration, this study will provide important information about force appreciation acuity in individuals with osteoarthritis of the knee joint. If force acuity deficits are found to exist between control and osteoarthritis groups, the methods utilised will further establish if these deficits are global, or localised to the region of joint pathology.

Whilst extracting information about force appreciation acuity in an osteoarthritic population is the primary purpose of this study, a dearth of previously published force appreciation studies involving older subject groups means awareness of force appreciation acuity in older adults is also limited. Therefore, this investigation will also enhance current understandings of force appreciation in older adults.

The findings from the current study will have significance for health professionals providing rehabilitation services to individuals with osteoarthritis. If changes in force appreciation are demonstrated in the osteoarthritis group, therapy strategies that incorporate 'force awareness' exercises may well optimise rehabilitation by reducing the risk of injury caused by under or overexerting muscles during exercises.

1.4 SCOPE OF THE STUDY

Although intended to examine force appreciation thresholds in osteoarthritic patients, the design of this study prevents identification of the structures and processes responsible for differences, should these be found. Likewise, recognition of differences does not equate to establishing appropriate rehabilitation strategies. If impaired discrimination levels are identified, further investigation will need to identify simple assessment techniques suited to

clinical use as well as safe and effective treatment techniques to address deficits in force appreciation.

2. LITERATURE REVIEW

This chapter is divided into four sections. The first section discusses the search strategy used, search returns, and includes a summary of the force appreciation studies considered in this review of literature. The second section includes an examination of terminology used to describe force appreciation and reviews current understandings of proprioception and, specifically, force appreciation. The third section describes the psychophysiological approaches used to investigate and measure sensory perception and force appreciation in humans. The fourth section reviews current understandings of human force appreciation in both healthy individuals and individuals experiencing pain and/or motor dysfunction.

2.1 Literature search: Force appreciation studies

Literature pertaining to force appreciation in human subjects and those studies that investigated force sense, force appreciation, force control or weight sense as the dependant measure were considered in this review.

2.1.1 Search inclusion criteria

The following criteria were used to determine which studies would be examined in the literature review.

- *In vivo* studies that used human participants.
- Studies that investigated force sense, force appreciation, force control or weight sense in voluntary muscle.
- Clinical trials that investigated the impact of interventions on force appreciation, including weight sense. Case reports were excluded due to their limited information and fundamental methodological errors.
- Associated studies of the physiology, morphology, structure, neurophysiology and psychology of proprioception and proprioceptors were included for background purposes.

2.1.2 Databases and resources searched

A search strategy was used to identify both published and unpublished studies and was limited to papers in the English language. Studies were located electronically using the following databases or resources:

- Allied and Complementary Medicine (AMED, 1985+)
- Cochrane Database of Systematic Reviews
- Cumulative Index to Nursing & Allied Health Literature (CINAHL, 1982+)
- Current Contents (1997+)
- EBSCO Health Databases
- Evidence Based Medicine Reviews
- Medline
- PEDro (Physiotherapy Evidence Database)
- Proquest
- Sports Discus
- Web of Science
- e-Journals
- Unpublished theses held in New Zealand and Australia

In addition the Internet was searched for information on force sense, force appreciation, force control, muscle sense, tension sense or weight sense. Reference lists of all included studies and texts were manually searched for further relevant studies that may have been missed using the search criteria.

2.1.3 Search terms used

For each database, a search strategy was used to identify studies relating to force appreciation. The search terms were modified as required for each database. Individual search terms were combined and phrases formed to target the desired studies and were used in the descriptors, title, abstract, and within the body of the text as listed in Table 2.1.

Table 2.1. Search terms used in the search

Search terms		
accuracy	human	posture
appreciation	in situ	precision
awareness	in vivo	pressure
contraction	isometric contraction	proprioception (tive)
control	judgment	sense (s)
detection	kinaesthesis (kinesthesis)	sensation
difference	kinaesthetic (kinesthetic)	sensory receptor (s)
differential threshold	load (s, ing)	sensory thresholds
discrimination	match (ing)	strength
exertion	mechanoreceptor (s)	stress
feedforward	motor activity	tension
feedback	movement	threshold (s)
force (s)	muscle	voluntary
force sensation	muscle contraction	Weber (s)
Golgi apparatus	osteoarthritis	weight
Golgi tendon organ	perception	weight perception

2.1.4 Search returns

The search strategy returned 51 studies suitable for review. Protocols reported in these studies included force matching, force estimation, force control and weight matching and/or estimation tasks.

2.2 Proprioception and force appreciation

This section defines proprioception and force appreciation and provides an overview of the peripheral, spinal and central structures occupied with the perceptual construction of 'force appreciation'.

2.2.1 Defining proprioception and force appreciation

Any motor output is a function of muscle position, body position, muscle length, stiffness, state of activation and metabolic adequacy (Jones, 1989b). Motor activity is the aggregate of actively produced internal forces and passively experienced external forces and relies on awareness of both motor output and of movement outcomes (de Graaf et al., 2004). Whilst simple motor outputs (including reflex actions) require no sensory feedback, complex motor activities depend on information received by the receptors of the sensory system for successful performance (Coran, Ward, & Enns, 1994).

Sherrington (1911) categorised sensory receptors as interoceptors (reactive to stimuli arising from internal organs); exteroceptors and teloceptors (reactive to immediate and distant external stimuli respectively); and proprioceptors which he defined as those receptors that react to information about the spatial and mechanical status of the musculoskeletal system (Stillman, 2002).

More specifically, Bastian coined the term 'kinaesthesia' in the late 19th century to describe the array of sensations that arise from, or are produced by movements (Bastian, 1888). Gandevia et al. (1992) in turn described three components of kinaesthesia: sensations pertaining to position and movement of joints; sensation of force, effort and heaviness; and the sensations pertaining to perceived timing of muscular activation.

While sensation is literally the recognition of single specific stimuli, proprioceptive discrimination is a construct derived from the assimilation of sensory inputs from a variety of sources including visual apparatus, vestibular organs, joint receptors, muscle receptors and skin receptors (Williams, Warwick, Dyson & Bannister, 1989a). The proprioceptive apparatus dispenses a sensory function — facilitating perception of spatial and mechanical stimuli, and an asensory function — assisting the subconscious regulation of movement, balance and posture (Cafarelli, 1982). This sensory modality has been variously labelled as proprioception, kinaesthesia, kinaesthetic awareness, body position sense and movement sense over time.

The sensory motor apparatus engaged in the construction of proprioceptive awareness uses multiple sensations to detect and encode changes in the spatial and mechanical status of the musculoskeletal system. Peripheral mechanoreceptors detect the onset of (or changes in) movement, tension, stretch, vibration and pressure, producing signals which are processed centrally to allow an individual to perceive velocity, position, stiffness, viscosity, mass, weight, friction, direction, shape, balance, inertia, and effort (Gandevia et al., 1992).

Thus far, investigations of proprioceptive systems have predominantly focused on movement and position sense with markedly less attention applied to the study of the sense of force, effort and heaviness (Jones, 1989b). Records of Sir Charles Bell's early investigations into 'force sensation' date back to the early 1800s (Jones, 1972; Lafargue, Paillard, Lamarre & Sirigu, 2003) and although investigated for nearly two centuries, the structures and mechanisms utilised by the central nervous system to encode force output are still poorly understood (de Graaf et al., 2004). To date, methods used to assess force appreciation include investigating the ability to match weights lifted or forces generated, the ability to estimate weights lifted or forces generated, the ability to sustain a desired submaximal force output, and the ability to discriminate between differing force levels (Carson et al., 2002; Jones, 1989; Jones, 2003; Proske et al., 2004).

Force appreciation is a loosely defined phrase that has in the past been used to describe both sensation and/or perception of effort, weight, load, stress, tension and work (Banister, 1979; Cafarelli, 1982; de Graaf et al., 2004; Jones, 1989b; Lafargue & Sirigu, 2002; McCloskey et al., 1974). Understanding how well an individual perceives the muscle forces they generate is hindered by a lack of accord in both the descriptors used when defining force appreciation and the investigative approaches used to assess this sensory modality (Cafarelli, 1982; Jones, 2003). Additional confusion arises because differing aspects of force sensation and force perception are often inadequately described within studies (Stillman, 2002). The poor definition of sensations-of-interest within a study and a lack of accord on force appreciation descriptors across studies affect both the quality of data arising from force appreciation studies and the development of a

comprehensive understanding of human muscle force appreciation. For example, both a rating of localised muscle effort as well as that of general exertion can be submitted as a rating of 'effort' by a poorly instructed subject (Burgess & Jones, 1997; McCloskey et al., 1974).

As many methods have been used to assess force appreciation, with each methodology promoting a different component of the proprioceptive apparatus, debate continues regarding the extent to which peripheral and central elements contribute to force appreciation. When generating muscle forces, cutaneous mechanoreceptors respond to pressure of any objects against the skin; muscle, tendon and joint mechanoreceptors respond to tissue loading; and motor efferents firing patterns provide corollary information (Jones, 2003; McCloskey et al., 1974). Resulting 'pressure' sensations, 'tension' sensations and 'effort' sensations enable individuals to differentiate inputs arising from cutaneous receptors, from peripheral intramuscular mechanoreceptors and those arising from central efferent outputs (McCloskey et al., 1974).

If mediated purely by peripheral receptors, force appreciation would originate from sensory receptors in the muscles, joints and skin. Historically this 'muscle sense' has been credited to the Golgi tendon organ; a muscle tension receptor (Binder, Kroin, Moore & Stewart, 1977; Chalmers, 2002; Swett & Schoultz, 1975). If centrally mediated, force appreciation would arise solely from corollary discharge of the cortical regions involved in muscle force generation (Carson et al., 2002; Takarada, Nozaki, & Taira, 2006).

Increasingly, the terms 'sense of tension' and 'sense of effort' have been used to differentiate between peripherally and centrally derived components of force appreciation (Burgess & Jones, 1997; Gandevia & McCloskey, 1977; Jones & Burgess, 1998; Lafargue et al., 2003; McCloskey, Gandevia, Potter & Colebatch, 1983; Van Doren, 1995). Specifically 'sense of tension' has been used to describe force awareness gained through sensory feedback from peripheral mechanoreceptors such as Golgi tendon organs and muscle spindles. In contrast 'sense of effort' describes the derivation of force awareness from cortical activity — specifically copies of efferent motor activity (McCloskey et al., 1974; Roland & Ladegaard-Pedersen, 1977). As both the

volume and variety of sensory information received and processed by the cortex increases, proprioceptive acuity is improved until a point of information saturation or redundancy is met when new sensory input no longer enhances proprioceptive acuity (Bahrick, Lickliter & Flom, 2004; Brodie, 1985; Brodie & Ross, 1985; Stillman, 2002).

In an attempt to minimise confusion in this thesis, the term 'force appreciation' will describe the proprioceptive system responsible for encoding and interpreting the magnitude of volitional muscle output. The term 'force acuity' alludes to how accurately an individual's perception of produced force matches their muscle's actual force output. The term 'force sense' is used in reference to force coding by peripheral mechanoreceptors, and 'force perception' describes centrally generated force coding.

2.2.2 Peripheral mechanoreceptors contributing to force sensation

Sensory endings involved in mechanoreception include muscle spindles, Golgi tendon organs, lamellated corpuscles (Pacinian, Paciniform, and Golgi-Mazzoni types), Ruffini endings, Merkel discs, Meissner's corpuscles and free nerve endings. These receptors relay information from muscles, tendons, ligaments, joints, skin and deeper tissues to the cortex via an array of afferent neural pathways (Kandel, Schwartz, & Jessell, 2000; Nyland, Caborn, & Johnson, 1998; Stillman, 2002; Williams, Warwick, Dyson & Bannister, 1989a). Functional role determines the type, density, distribution, and development of mechanoreceptors within muscles, joints and skin (Nyland et al., 1998). These 'muscle', 'joint' and 'cutaneous' receptors are all activated to varying extents during production of active muscle tension (Jones & Piateski, 2006). It is probable that these three receptor groups provide, in parallel, feedback that is compared to the centrally generated motor command to enable force appreciation as many studies have shown that inhibition of muscle and joint receptors in isolation and in combination does not significantly impair force appreciation (Cafarelli, 1982; Carson et al., 2002; Ebied, Kemp, & Frostick, 2004; Jones & Hunter, 1982; Macefield, 2005; Monzee, Lamarre, & Smith, 2003; Nicolas, Marchand-Pauvert, Lasserre et al., 2005; Proske, 2006;

Williams, La Pointe, & Blanton, 1984a; Williams, La Pointe, Mahan et al., 1984b).

2.2.2a Muscle receptors

The question of muscle 'sentience' has been debated for well over 175 years (Matthews, 1982). One of the early proponents of a 'muscular sense' was the neurologist Sir Charles Sherrington, who proposed the perceptions of muscular sense be grouped into those of posture, of passive movement, of active movement, and of resistance to movement (Sherrington, 1911). Sherrington further suggested that changes in consciousness accompany all movements of the body which occur above a certain *liminal* (barely perceptible) amount, and over distances beyond a *liminal* extent (Sherrington, 1911).

Five groups of muscle (including muscle belly, musculotendinous junction, tendon and associated connective tissue) receptors have been demonstrated to provide kinaesthetic information which encodes force and movement parameters: Golgi tendon organs, muscle spindles, Ruffini corpuscles, lamellated corpuscles, and free nerve endings.

The Golgi tendon organ

Golgi tendon organs are intramuscular tension receptors comprising slender, short capsules situated almost exclusively within the musculotendinous junction of skeletal muscles (Józsa, Balint, Kannus, Järvinen & Lehto, 1993). Within a fibrous capsule, mechano-sensitive terminals of large diameter well-myelinated Ib fibres intertwine with collagen bundles to form the Golgi tendon organ, discharging when deformed by the development of intramuscular tension (Eccles, Eccles, & Lundberg, 1957; Spielmann & Stauffer, 1986).

Golgi tendon organs are generally connected in series with extrafusal muscle fibres, although Spielmann and Stauffer (1986) have demonstrated the existence of Golgi tendon organs in parallel with extrafusal fibres. The majority of Golgi tendon organs are coupled with no more than 25 extrafusal muscle fibres arising from multiple motor units (Jami, 1992). Only one or two muscle fibres of an individual motor unit insert into a given tendon organ, with motor

units often having connections to several Golgi tendon organs (Davies, Petit, & Scott, 1995; Gregory & Proske, 1981). A Golgi tendon organ will be connected to both slow and fast twitch muscle fibres, the exact proportion of which is dependent on the motor units feeding into the Golgi tendon organ (Mileusnic & Loeb, 2006).

Golgi tendon organs are very sensitive to tension generated by active muscle contraction and will respond vigorously even to contractions generated by single motor units (Crago, Houk, & Rymer, 1982; Gregory & Proske, 1979). The response of a Golgi tendon organ to increased muscle tension is dependent on both the total tension generated and the rate of change of tension generation (Davies et al., 1995). When activated by muscle fibre contraction, tendon organ discharging shows an initial peak in firing rate (dynamic response) decreasing to a plateau level (static response) if the contraction is maintained (Davies et al., 1995). Whilst Golgi tendon organs can be activated by muscle stretch, this 'passive tension' activation threshold is very high and responses are sluggish (Józsa et al., 1993). In contrast, studies involving animals have established that Golgi tendon organs can accurately signal rises in passive tension which arise from eccentric exercise-induced muscle damage (Gregory, Morgan, & Proske, 2003).

As active tension receptors, the Golgi tendon organ is a primary candidate for the encoding of force output. However, evidence of a non-linear relationship between Golgi tendon organ discharge and both individual and collective muscle fibre force outputs exists (Harrison & Jankowska, 1985a, 1985b; Mileusnic & Loeb, 2006) suggesting that Golgi tendon organs in isolation do not provide accurate information about the degree of tension generated by muscle contractions.

Whilst Golgi tendon organs respond vigorously to single motor unit contractions, both Crago et al. (1982) and Gregory and Proske (1979) demonstrated that the cumulative Golgi tendon organ response during episodes of multiple motor unit stimulation is lower than the sum of individual Golgi tendon organ responses. Gregory and Proske (1979) also demonstrated that Golgi tendon organ response is not affected by the type of motor unit being activated, with motor

units comprising of slow-oxidative fibres (slow-MU) producing similar Golgi tendon organ responses to those produced by the fast-oxidative and fast-glycolytic fibre motor units (fast-MU). In the Gregory and Proske study (1979), similar Golgi tendon organ firing intensities were produced by a slow-MU generating 0.8g of tension and a fast-MU producing 31g of tension. Additionally, Golgi tendon organ activity is dependent on the recruitment order of inserting muscle fibres (Mileusnic & Loeb, 2006). Reductions in the dynamic response of a Golgi tendon organ to increased tension has been demonstrated as a result of previous activation of a muscle fibre (self-adaptation) and by activation of a different muscle fibre within the same Golgi tendon organ (cross-adaptation) (Gregory & Proske, 1979).

The inability to demonstrate a linear relationship between tension development and Golgi tendon organ firing patterns suggests that force encoding is not solely reliant on the Golgi tendon organ. Instead, the primary role of the tendon organ is proposed to be the prevention of muscle damage arising from excessive force generation through the mechanism of autogenic inhibition (Chalmers, 2002; Harrison & Jankowska, 1985a; Jami, 1992). Studies involving animals and humans have demonstrated that Golgi tendon organs, initially thought to be solely inhibitory in nature, can have both inhibitory and excitatory effects on homonymous and synergist motor neurons (Gregory, Brockett, Morgan, Whitehead & Proske, 2002; Prochazka, Gillard, & Bennett, 1997).

Golgi tendon organ firing patterns appear stable in the presence of acute muscle dysfunction. Studies involving animals have shown that Golgi tendon organs reliably signal muscle tension even in the presence of acute fatigue or eccentric exercise-induced muscle damage (Gregory et al., 2002; Gregory, Morgan & Proske, 2003). In contrast, chronic muscle change alters human Golgi tendon organ characteristics. A reduction in both muscle spindle and Golgi tendon organ size and numbers has been demonstrated after injury and disuse (Józsa, Kannus, Järvinen, Balint & Järvinen, 1996; Scott, Petit, & Davies, 1996). The discovery of a significant positive correlation between Golgi tendon organ firing rates and muscle fibre cross-sectional area for both total motor unit cross-sectional area and especially the cross-sectional area of individual muscle fibres connected in series to the proximal end of the Golgi

tendon organ by Spielmann and Stauffer (1986) also suggest that Golgi tendon organ function could be affected in chronic musculoskeletal conditions where muscle atrophy is evident.

The Golgi tendon organ forms part of the autogenic inhibition reflex loop (Chalmers, 2002; Jami, 1992). Autogenic inhibition is a disynaptic reflex arc involving one interneuron and two synapses between the afferent Golgi tendon organ and the motor neuron. Jami (1992) describes autogenic inhibition as the inhibitory influence on homonymous motor neurons — produced by Golgi tendon organs that have been stimulated by contraction of the first recruited motor units — such that further recruitment is restrained and muscle contraction progresses smoothly.

The muscle spindle

Muscle spindles are rapidly responding intramuscular receptors that are composed of small numbers of intrafusal muscle fibres (Burgess, Wei, Clark & Simon, 1982). These intrafusal muscle fibres are encapsulated within a connective tissue capsule and are innervated by both motor and sensory nerve fibres (Edin & Vallbo, 1990a; Józsa, Kvist, Kannus & Järvinen, 1988). The intrafusal fibres are aligned parallel to extrafusal muscle fibres and as such are highly responsive to muscle fibre elongation (Edin & Vallbo, 1990b). Movement parameters including extent, direction and velocity of movement are encoded by muscle spindle firing patterns (Winter, Allen, & Proske, 2005). Motor innervation of the muscle spindle effects an alteration in intrafusal motor fibre length influencing the responsiveness of muscle spindles to elongation (Wilson, Gandevia, & Burke, 1995). Whilst muscle spindles are not specifically responsive to intramuscular tension, it is probable that feedback to the cortex, regarding muscle forces generated, is a function of the interplay of Golgi tendon organ and muscle spindle responses (Goodwin, McCloskey, & Matthews, 1972).

Other intramuscular proprioceptors

Ruffini corpuscles and lamellated corpuscles receptors (group II and III afferents) are present in the connective tissue surrounding tendons and musculotendinous junctions (Józsa et al., 1993: Stillman, 2000). Ruffinian

corpuscles are found on both muscle and tendon sides of the musculocutaneous junction whereas lamellated corpuscles are predominantly found on the tendon side (Bistevins & Awad, 1981; Józsa et al., 1993). Józsa et al. (1993) demonstrated Ruffini and lamellated corpuscles and Golgi tendon organs present in human palmaris longus and plantaris muscles at a ratio of 1:2:2 respectively. Lamellated corpuscles, responsive to pressure, have been found in quantities four times that of Golgi tendon organs (Bistevins & Awad, 1981). Ruffinian corpuscles are low threshold, predominantly slowly adapting mechanoreceptors responsive to both static and dynamic tension that signal limb position (Macefield, 2005; Stillman, 2000). In contrast lamellated corpuscles are low threshold, rapidly adapting mechanoreceptors responding to vibration and dynamic (changing) pressure with some evidence suggesting the rapid adaptability of these receptors assists the sensing and coding of velocity and limb movement (Józsa et al., 1993; Józsa et al., 1996; Stillman, 2000).

Finally, small diameter free nerve endings (group III and IV afferents) are distributed throughout muscle bellies, tendons and connective tissue sheaths and respond to moderate painful and non-painful muscle stretch and/or contraction (Goodwin et al., 1972; Graven-Nielsen & Mense, 2001; Grigg, Schaible, & Schmidt, 1986; Hayes, Kindig, & Kaufman, 2005; Józsa et al., 1996; Lobenhoffer, Biedert, Lattermann, Gerich & Müller, 1996; Rossi & Decchi, 1995). Stillman (2000) states that almost 80% of all muscle afferents arise from free nerve endings in a 2:2:1 ratio of nociceptive mechano-, thermo- and chemical receptors; non-nociceptive pressure and contraction receptors; and non-nociceptive thermoreceptors. A considerable proportion of these free nerve endings are responsive to more than one form of stimuli (Hayes et al., 2005; Mense & Meyer, 1985; Stillman, 2000) and many are sensitised by the chemical by-products of inflammation, ischaemia and fatigue including lactic acid, prostaglandins, and bradykinins (Darques & Jammes, 1997; Wenngren, Pedersen, Sjölander, Bergenheim & Johansson, 1998). It has been proposed that these 'sensitised' free nerve endings modulate gamma motor neuron firing which in turn distorts position and movement sense (Brunetti et al., 2003; Capra & Ro, 2000), however there is no data published to date on the influence of free nerve endings on muscle tension sense.

2.2.2b Joint receptors

Mechanoreceptors within the knee have been found in the joint capsule, menisci, periosteum and ligaments (Macefield, 2005; Stillman, 2002; Williams et al., 1989a). Four types of receptors have been found in ligaments: Ruffini corpuscles — slow adapting mechanoreceptors that respond to stretch; Vater-Pacini corpuscles — rapidly adapting low threshold receptors sensitive to movement and pressure; Golgi corpuscles — high threshold slow adapting mechanoreceptors that respond to pressure; and free nerve endings — high threshold slow adapters which react to noxious stimuli (Franchi, Zaccherotti, & Aglietti, 1995). Muscle afferents have been demonstrated to significantly enhance 'joint position' and 'joint movement' sense (Gandevia & McCloskey, 1976; Laufer, Hocherman, & Dickstein, 2001), but little is known about the influence of joint afferents on 'muscle tension' sense. Studies involving animals have demonstrated that joint receptors can have a facilitatory effect on the reflex pathways of Ib afferents (Golgi tendon organs) (Lundberg, Malmgren, & Schomburg, 1978). Lundberg et al. (1978) suggested that this facilitation of Ib reflex pathways induces a protective decrease in muscle tension as terminal joint range is approached. Whilst this result demonstrated that joint afferents can influence muscle tension, little research has been conducted regarding joint afferents' influence on conscious muscle force awareness. Williams et al. (1984b) have demonstrated that isolated anaesthetisation of temporomandibular joint afferents does not impair human bite force discrimination. No studies regarding the influence of human knee joint afferents' influence on force appreciation have been published.

2.2.2c Cutaneous receptors

Sensory endings including Merkel's receptors, Ruffini corpuscles, Meissner's corpuscles, hair receptors and some free nerve endings function as cutaneous mechanoreceptors that respond to pressure and touch (Williams et al., 1989a). Whilst not specifically providing information about the degree of force generated within a muscle, pressure receptors can register skin deformation as a result of muscle contraction (Jones & Piateski, 2006). Additionally, as with joint receptors (Lundberg et al., 1978), cutaneous receptors have been shown to facilitate Ib

reflexes in studies involving animals (Lundberg, Malmgren, & Schomburg, 1977). Cutaneous receptors are almost certainly involved in compiling a global assessment of forces generated as they provide a reference signal that a task is being performed in the presence of externally applied forces (Gandevia et al., 1992; Monzee et al., 2003). This notion is supported by evidence that in the hand, cutaneous receptor inhibition has been demonstrated to significantly (p<0.05) impair force matching and weight estimation tasks (Jones & Piateski, 2006; Kilbreath, Refshauge, & Gandevia, 1997). Cutaneous feedback from palmer receptors (at the point of contact with the testing apparatus) has been shown to influence force appreciation during contralateral matching tasks (Jones, 2003).

2.2.3 Spinal pathways for force sensation

Most sensory neurons give off multiple collateral nerve fibres which synapse with motor neurons, spinal interneurons, and ascend in a variety of neural tracts (e.g. the posterior column-medial lemniscus pathway, spinothalamic tracts) (Wolfe, Kluender, Levi et al., 2006). As such, the information garnered by sensory receptors travels along multiple spinal pathways and provides input to a variety of cortical and subcortical regions. Sensory information primarily travels along the posterior column-medial lemniscus pathway, spinothalamic tracts and spinocerebellar tracts (Mathews, 1982; Stillman, 2002; Williams et al., 1989a).

The most often-reported role of the posterior column-medial lemniscus pathway is to carry sensory information related to touch, pressure, vibration, stereognosis, two-point discrimination and proprioception to the sensorimotor cortex (Gandevia & McCloskey, 1976; Gordon & Ghez, 2000; Harrison & Jankowska, 1985b; Lackner & Levine, 1979; Proske, 1981; Sanes & Shadmehr, 1995; Wolfe et al, 2006). Primary sensory neurons arising from sensory receptors in the periphery enter the posterior column of the spinal cord and travel upwards via the fasciculus gracilis (levels below T6) or fasciculus cuneatus (levels above T6) to synapse in the nucleus gracilis or nucleus cuneatus of the medulla (Williams et al., 1989a). These secondary neurons travel via the medial lemniscus to synapse in the ventral posterolateral nucleus

of the thalamus and from there tertiary neurons proceed via the internal capsule to the primary somatosensory cortex (Williams et al., 1989a).

The spinothalamic tract signals temperature, pain, touch and pressure and are comprised of collaterals of touch and pressure-sensitive fibres ascending in the posterior columns, as well as mechano-receptive, thermo-receptive, and nocioceptive fibres of the lateral division of the dorsal root (P. Wiliams et al., 1989). It is the primary pathway for conscious pain and temperature information as well as providing an alternate pathway by which mechanoreceptive input reaches the thalamus and cerebral cortex (Wolfe et al., 2006). Unlike the posterior column-medial lemniscus pathway fibres, spinothalamic fibres synapse at or near the level of insertion to the spinal cord (Williams et al., 1989a). Secondary neurons conveying proprioceptive information travel via the anterior or lateral spinothalamic tracts to synapse in the ventral posterior lateral nucleus of the thalamus. As with the posterior column-medial lemniscus pathway, tertiary neurons of the spinothalamic tracts proceed via the internal capsule to the primary somatosensory cortex (Williams et al., 1989a).

Originating in the spinal cord and terminating in the ipsilateral cerebellum, the spinocerebellar tracts convey subconscious proprioceptive information to the cerebellar cortex (Bosco & Poppele, 2001). Proprioceptive information reaches the cerebellum directly via the spinocerebellar tracts and the cuneocerebellar tract and indirectly by way of the reticular formation (Bosco & Poppele, 2001; Williams et al., 1989a). This subconscious sensory information is conveyed along collaterals of primary sensory fibres which synapse on neurons of the nucleus dorsalis (lower thoracic segments and below) or lateral cuneate nucleus (upper thoracic segments and above). Secondary neurons travel via the anterior and posterior spinocerebellar (nucleus dorsalis) or cuneocerebellar (lateral cuneate nucleus) tracts to synapse within the cerebellum (Bosco & Poppele, 2001).

Of the receptors discussed in the previous section, the most often reported peripheral agent of force sense remains the Golgi tendon organ. Sensory information from Golgi tendon organs is transmitted along type Ib afferent fibres to the dorsal horn of the spinal cord (Gordon & Ghez, 2000). Type Ib afferents

are characterised by numerous collateral projections that synapse with a variety of spinal interneurons to influence motor neuron excitability locally, and at spinal levels above and below insertion (Lundberg et al., 1977; Rossi, Mazzocchio & Parlanti, 1991). Additionally, fibres project to the brainstem, cortex and cerebellum via the posterior column-medial lemniscus pathway, spinothalamic tracts and spinocerebellar tracts (Lundberg et al., 1978; Macefield, 2005; Rossi et al., 1991).

2.2.4 Cortical regions contributing to force appreciation

Normal muscle activity is either reflexive (protective, e.g. nociceptive withdrawal reflex; automatic, e.g. scratching) or purposeful (e.g. reaching for a cup). Whilst proprioceptive feedback aids the control of muscle forces and movement parameters via reflex and central connections (Park, Toole, & Lee, 1999), it is increasingly accepted that cortical corollary discharges are a significant 'feedforward' source of motor awareness (Cafarelli, 1982; Ghez, Hening, & Gordon, 1991; Gibson & McCarron, 2004; Hampson, Gibson, Lambert & Noakes, 2001; Kuo, 2002). Supraspinal involvement in the encoding of muscle force parameters therefore appears to be two-fold. Firstly the brainstem, cerebellum and cortex collect and collate information from peripheral receptors (feedback) and secondly by generation of predictive efferent copies of motor commands (feedforward) to quantify and qualify motor performance (Carson et al., 2002; Prochazka et al., 1997; Sanes & Shadmehr, 1995; Tunik et al., 2003).

Studies involving primates have revealed differences in the way the motor cortex codes movement and force (Sergio, Hamel-Paquet, & Kalaska, 2005). Georgopoulos, Schwartz and Kettner (1986) found that the direction of a movement is uniquely encoded by the population of corticomotor neurons activated to produce a movement. Individual neuronal 'movement vectors' were calculated from the activity patterns of motor neurons during performance of specific upper limb reaching tasks by rhesus monkeys (Georgopoulos et al., 1986). Within an activated neuronal population, the weighted sum of those vectors dictated the net direction of limb movement. Therefore, coding for movement was, in the main part, determined by *which neurones* were firing at any point in time (Georgopoulos et al., 1986). In contrast, it has been

demonstrated that individual corticomotor neurons are not tuned to force parameters (Georgopoulos & Ashe, 1992; Sergio et al., 2005). Supraspinal coding of force parameters is a product of *how many neurones* are activated and *how rapidly* they are firing at any given time, as well as *how the firing pattern changes* (e.g. tonic versus phasic discharge patterns) (Elder, Bradbury & Roberts, 1982; Georgopoulos & Ashe, 1992). As a rule, motor units are recruited in order of size. *Henneman's size principle* (Henneman, Somjen & Carpenter, 1965) states that motor units are typically recruited in order from smallest (least fibres) to largest (most fibres). In heterogeneous muscle, containing a mix of motor unit types, low levels of force output are provided primarily by low threshold, smaller slow-oxidative motor units. As more force is needed, progressive recruitment of higher threshold fast-oxidative and fast-glycolytic motor units occurs (Henneman, Somjen & Carpenter, 1965). It is probable that the cortical coding process includes a comparison of the types of motor unit activated for a given task.

The motor cortex can be divided into a primary and multiple secondary motor areas. The primary motor cortex generates neural impulses that control the execution of movement and is involved in both low-level planning of kinetic output and higher-level planning of kinematic output (Sergio et al., 2005). Secondary motor areas encompass all the cortical regions that influence motor output of the primary motor area and the spinal cord (Chouinard & Paus, 2006). Secondary motor regions include the posterior parietal cortex, which transforms visual information into motor commands; the premotor cortex, which is involved in the planning of movement based on sensory input received from the cerebellum; and the supplementary motor area, which is responsible for planning and coordinating complex motor activities. The temporal lobes are also implicated in force control (Jones 1989a). Other subcortical regions involved in motor function include the cerebellum and subcortical motor nuclei of the basal ganglia (Bosco & Poppele, 2001; Dettmers, Lemon, Stephan, Fink & Frackowiak, 1996; Fellows, Noth, & Schwarz, 1998; Lafargue & Sirigu, 2002).

The primary motor cortex has a direct influence on muscle activation whereas secondary motor regions all have direct but weak connections to motor neurons (Chouinard & Paus, 2006). Secondary motor areas have substantially more

inter-cortical connections than the primary motor cortex reflecting the role these areas play in planning movements, and the processing and interpretation of sensory cues (Chouinard & Paus, 2006; Georgopoulos & Ashe, 1992; Williams et al., 1989a).

The term 'efference copy' refers to the pattern of motor neuronal firing initiated and sustained by the motor cortex when a muscle is activated. It has been shown that feedforward efference copies are generated in the supplementary motor area (Haggard & Whitford, 2004). It has been suggested that an efference copy is used to predict the sensory consequences of motor commands (Blakemore, Wolpert, & Frith, 1998). The inability to tickle one's self has increased understanding of this neural prediction effect. In a study investigating self-induced versus externally-induced tickling, Blakemore et al. (1998) found greater somatosensory cortical and cerebellar responses to externally produced tickling suggesting that a degree of somatosensory suppression occurs during purposeful movement. Further to this, Haggard and Whitford (2004) investigated perceived finger muscle twitch magnitude in healthy adults. Transcranial magnetic-stimulation-generated motor-evoked potentials were perceived to be smaller when subjects were actively contracting their finger flexors, confirming a process of sensory suppression. This effect was virtually ablated by a pre-pulse to the supplementary motor area indicating that this region of the cortical motor apparatus is responsible for generating motor efferent copies (Haggard & Whitford, 2004).

Functional MRI has been used by de Graaf et al. (2004) to map the sensorimotor cortex while subjects performed motor tasks of similar output intensity (e.g. loading torque, movement direction). Subjects (n=15) attended, in the first part, to perceptions of the muscle forces employed (kinetic outcomes) and secondly to perception of movement effects (kinematic outcome). During reference trials subjects performed rhythmical hand movements whilst attending to either force parameters (how hard to push) or movement parameters (amplitude and frequency of movement). Subjects then repeated the task against a higher external force whilst attempting to match force output or movement quality. Subjects all reported considerable difficulty performing the force matching condition. Both the number and size of cortical zones activated

during force tasks were substantially larger than those seen during the movement tasks. Force tasks stimulated the posterior insula, primary sensorimotor areas and associative somatosensory areas significantly more than the 'movement' tasks. The greater involvement of the sensory cortex suggested that efferent output mapping alone was insufficient for the encoding of force. These findings reinforce Cafarelli's supposition (Cafarelli, 1982) that force may not be encoded by motor command, but rather from the neurophysiological strategies employed to maintain adequate motor output.

Lesions involving the frontal cortex evoke a variety of motor deficits in humans and primates (Freund & Hummelsheim, 1985; Passingham, Perry, & Wilkinson, 1978). Jones (1989a) investigated force coordination patterns in subjects with frontal cortex lesions (induced to relieve focal cerebral seizures). Subjects (n=64) were instructed to generate target forces using isometric contractions at levels representing 10%, 20%, 30% and 40% MVC with a designated finger or fingers pushing on a test device fitted with individual strain gauge force transducers recording the force generated by individual fingers. Variables of interest were absolute error and time taken to reach the target level. Absolute errors were similar in all groups for all levels, but significant ($p<0.05$) differences in the time taken to reach the target level were identified for the subgroup that had had excisions involving the right fronto-temporal cortex. This effect became more pronounced as task complexity increased (single versus multiple finger tests). The frontal lobe houses the primary and secondary motor areas that generate efferent copies of descending motor commands; the temporal lobe is involved in the integration of information from multiple sources. Combined fronto-temporal lesions would therefore have affected both feedforward and feedback mechanisms. Isolated lesions in each of these areas did not impair force coordination, suggesting that the cortex can utilise either mechanism to code force. Jones' findings suggest that during more complex tasks, the cortex relies on both feedforward and feedback data for force coding. Some aspects of motor control are preferentially controlled by left or right sides of the brain; motor sequencing by the left cerebral hemisphere (Kimura, 1977) and motor persistence by the right cerebral hemispheres (Kertesz, Nicholson, Cancelliere, Kassa & Black, 1985). Deficits in force coordination in the fronto-temporal group were evident in both hands but were markedly more pronounced in the left

hand. As there were no subjects with left fronto-temporal lobe excisions available for study, conclusions about the relative importance of right versus left fronto-temporal contribution to force coding were not possible.

The basal ganglia also plays a role in the generation of sense of effort during motor tasks as demonstrated by Lafargue et al. (2002), who examined weight matching acuity in subjects with and without Huntingdon's disease. Huntingdon subjects and controls undertook a weight discrimination task using index fingers with both reference and comparison loads weighing 280g. Comparison loads were subsequently altered by increments of 20g until a subject correctly identified a change in load with both 'increasing' and 'decreasing' runs executed to derive upper and lower threshold values. The discrimination threshold was derived by averaging the upper and lower threshold values. Healthy subjects slightly overestimated weights, producing comparison weights that were on average 7.2% heavier than reference weights. Huntingdon's patients slightly underestimated reference weights by 6.6%. Another major difference between groups was revealed by comparing the interval between upper and lower discrimination thresholds. Huntingdon's subjects produced an interval almost seven times larger than that of the comparison subjects (p<0.05). These findings confirmed that basal ganglia are involved in the awareness of forces generated.

2.2.5 Comparisons of central and peripheral contributions to force coding

As stated earlier, the superiority of central versus peripheral contributions to force coding is still being established. The following studies outline research attempting to differentiate the relative contributions of peripheral and central mechanisms to force coding.

Early work by McCloskey et al. (1974) utilised a weight estimation methodology and vibration in an attempt to differentiate between peripheral and central contributions to muscle force awareness. Vibrating muscle tissue at frequencies between 30 and100 Hz activates muscle spindles and induces a muscle contraction. This 'tonic vibration reflex' has been used to explore peripheral versus central force coding mechanisms (Cafarelli & Kostka, 1981; Cafarelli &

Layton-Wood, 1986; Goodwin et al., 1972; McCloskey et al., 1974). In the McCloskey study (1974), peripheral afferents were deemed to contribute to a localised and muscle centred 'sense of tension' with centrally generated efferent copies believed to produce a more global 'sense of effort'. Subjects performed isometric elbow flexion against a strain gauge (loads between 1 and 5kg) and were variously instructed to *'Keep your effort constant'* or *'Keep the tension in the cable constant'* throughout the contraction. Sensory input from cutaneous afferents was eliminated through anaesthetisation. Vibration was applied to the contracting biceps or antagonist triceps muscle once a steady contraction was established. When maintaining a constant effort, vibration of the biceps brachii tendon induced an increase in strain gauge readings which was maintained throughout the 5-second vibration period. In contrast, strain gauge readings initially rose on vibration during the constant-tension trials, but subjects generally adjusted their output to pre-vibration levels before vibration was terminated. On termination of the vibration in 'tension' trials, strain gauge readings dropped below pre-vibration levels, and again this was corrected by subjects in most instances. This result suggests that the primacy of peripheral versus central contributions to force coding is, in part, a function of the demands of the matching tasks and therefore the nature of 'attention' paid to the force task. A third of the test subjects failed to adjust their output on the constant-tension trials whilst reporting the perception that they had successfully maintained the target tension. McCloskey et al. (1974) proposed that these subjects were able to switch from a tension matching to effort matching strategy during the course of vibration during constant tension tasks.

Paradigms supporting the notion that sense of effort has a central origin, rather than being derived from peripheral feedback, include the following findings: force matching deteriorates as muscle function is impaired as evidenced by studies of fatigue and curarisation (Abraham & Craig, 1975; Gandevia & McCloskey, 1977; McCloskey et al., 1974; Rubley, Denegar, Buckley & Newell, 2003); movement but not force illusions are induced when peripheral mechanoreceptors are stimulated (Gelfan & Carter, 1967; McCloskey, Cross, Honner & Potter, 1983); and sense of effort persists in subjects with movement-related proprioceptive deficits and hemiparesis (Gandevia et al., 1992; Lafargue et al., 2003; Lafargue & Sirigu, 2002; Raj, Ingty, & Devanandan, 1985).

Abraham and Craig (1975) investigated the ability to maintain levels of motor output over time during handgrip tasks. Subjects performed sustained submaximal grips (15%, 30%, 50% MVC with duration of 60 seconds, 70% MVC with duration of 30 seconds) with and without visual feedback. All subjects were able to produce target outputs with visual feedback, but in the absence of visual cues, tension consistently decreased over the duration of the trial. A positive correlation between starting load and rate of tension decline was demonstrated. In the un-cued trials, surface EMG recordings reduced and tension declined over the length of the contraction. Minimising input from cutaneous afferents did not affect a change in the extent or rate of tension decline. In the cued trials, surface EMG readings increased as tension was maintained indicating that muscle fatigue was occurring in this condition. The authors suggested that sensory accommodation accounted for the decline seen when visual cues were absent. The reduced EMG readings in the un-cued condition corresponded with the decline in motor output occurring in the absence of visual feedback. Numbing the hand failed to produce a change in tension decline indicating that sensory inhibition from cutaneous afferents did not occur. As these were submaximal contractions, neuromuscular junction fatigue was unlikely to have accounted for the reduction in motor unit firing. Inhibition from mechanoreceptors within the muscle may have prompted the tension decline. Abraham and Craig suggested that Golgi tendon organ mediated autogenic inhibition accounted for the tension decreases demonstrated. Failure to maintain tension in the un-cued condition reinforces the findings of Gelfan and Carter (1967) that muscle mechanoreceptors provide subconscious awareness of muscle forces only. Visual input was required to maintain conscious awareness of motor output reinforcing the notion that both feedforward and feedback mechanisms are important for force appreciation (Cafarelli, 1982; Jones, 1989b).

In the McCloskey et al. (1974) study discussed earlier, the researchers also investigated the effect of induced fatigue on weight matching accuracy at the elbow and index finger. With elbows flexed at 90˚ flexion, subjects lifted weighted reference loads (9lb) and weighted comparison loads simultaneously. Subjects rated comparison loads as lighter, heavier or equal in weight compared to reference loads with comparison loads subsequently increased or

decreased on the instruction of subjects until buckets were perceived to be of equal weight. This protocol was repeated with the index finger flexion using a trigger-pulling action to lift reference and comparison loads. In the non-fatigue condition, subjects rested between matching trials. In the fatigue conditions subjects sustained a 9lb reference bucket for 8–16 minutes for the elbow and an 18lb hold for up to two minutes followed by an (above elbow) sphygmomanometer-cuff-induced temporary ischaemia lasting up to four minutes for the index finger tests. McCloskey et al. reported finding considerable variation in weight matching across subjects; however all subjects demonstrated significantly different matching weights for unfatigued versus fatigued muscles. Extracted relative scores (see Appendix 2) for weight matching at the elbow were 1.06 at two minutes, 1.33 at five minutes and 1.67 at 10 minutes in the fatigue condition where the reference arm supported its weight continuously. In contrast, relative scores of 0.89, 0.89 and 1.00 were obtained at two, five and ten minutes when the reference arm was rested between trials. Extracted relative scores for index finger tests were 0.00 in the non-fatigued condition and 1.34 after fatigue was induced. Subjects reported experiencing difficulty matching weights in the absence of appreciable movement for both elbow and finger protocols. These results indicated that fatigue induced a perception of increased effort during weight matching that manifests as a tendency to overestimate the weights of lifted objects. During maximal contractions the motor pool of a muscle is most often fully activated and fatigue produces a steady reduction in motor activity as contractile elements fail; however, during submaximal motor activity, fatigue produces an increase in motor unit firing to accommodate the partial failure of already recruited motor units (Cafarelli, 1988). This latter process would produce a 'larger' efferent copy but not increase peripheral mechanoreceptor discharge as muscle tension decreases rather than increases during fatigue and Golgi tendon organs become markedly less responsive (Hutton & Nelson, 1986). The increase in Weber's fractions as fatigue progressed indicated that subjects were matching feedforward efferent copy rather than peripheral mechanoreceptor feedback; a finding that further reinforces the pre-eminence of central cues in the perception of generated muscle forces.

Cafarelli and Layton-Wood (1986) explored the effect of vibration on fatigued quadriceps muscles. Immediately after bouts of fatigue-inducing exercise, healthy subjects performed contralateral force matching tasks with and without vibration of the fatigued leg (reference level 50% MVC). Fatigue was induced by rapidly performing sets of maximal contractions until subjects were unable to continue. In fresh muscles, vibration produced an increase in perceived force with subjects overestimating force as described previously. The relative score for unfatigued non-vibrated muscles at 50% MVC was 0.74. After vibration of unfatigued muscles, the relative score was 0.94. As subjects fatigued, both vibrated and non-vibrated conditions demonstrated similar degrees of force overestimation. Relative scores extended to 1.10 after the fifth set of fatiguing contractions in both vibrated and non-vibrated states suggesting that force overestimations induced by fatigue and vibration were not cumulative. These findings showed that fatigue attenuated the effect of vibration on force encoding. The authors argued that 'the effects of vibration were sufficient to alter force sensation but they are probably *not necessary* for force sensation'. This finding suggests that human beings tend to produce comparison forces that require the same level of motor pool activation as that needed to generate the reference force.

This study offered further insight into force encoding through the analysis of the matching forces produced. Electromyography readings showed that levels of motor pool activation increased in order to match the 50% MVC target. Accepting the eminence of feedforward force encoding, it is reasonable to assume that subjects encode the '50%' target according to the real time maximum capacity of the muscle performing the contraction. Subsequent matching values, expressed as a percentage of the comparison muscle maximal capacity, should therefore correspond to the true submaximal intensity of the reference contraction. It is interesting then that this was not demonstrated in the Cafarelli and Layton-Wood (1986) study described above. Pre-test maximal capacity was 522N and 454N for right (reference) and left (comparison) quadriceps muscles respectively. The non-fatigued, non-vibrated matching force was 37% of the right maximum capacity but actually represented 43% of the left maximum capacity (the vibrated match represented 54% of the left maximum). The right quadriceps maximal capacity reduced to 65% of its

pre-test maximum after fatigue so that the 50% pre-fatigue test level actually corresponded to 77% of the post fatigue maximum. The 55% match force produced after induction of fatigue corresponded to 63% of the left maximal capacity (assuming left maximum unchanged throughout testing). These values weaken the assumption that force is encoded primarily from the volume of motor efferent outflows. To this end, Cafarelli and Layton-Wood argued that force appreciation was derived by tracking the modifications made to a central command rather than the central command itself. If this is the case, then a centrally generated efferent copy supplies information regarding cortical motor neuronal activation as well as the cortical interneuronal activity which influenced cortical motor neuron firing.

The impact of cryotherapy on force control in the human hand was assessed using isometric grip force variability before and after 15 minutes' immersion in a 10˚C iced water bath (Rubley et al., 2003). Sensation tests were performed on healthy adults before and after ice immersion and after sustained submaximal isometric force tests (10%, 25% and 40% MVC). Using a fingertip pinch grip protocol, subjects attempted to match forces they generated over a 30-second period with a target force output displayed on a computer monitor. Accuracy (derived from root mean square errors) and precision (derived from standard deviation) were used to describe force variability. Rubley et al. reported that accuracy increased and precision decreased significantly ($p<0.05$) and similarly as target forces increased for both iced and non-iced conditions. Additionally tactile sense of pressure but not 2-point discrimination was altered by cryotherapy. The lack of cryotherapy effect on force variability is at odds with studies that have demonstrated impaired force awareness with cutaneous anesthetisation. When considering these results it should be noted that fifteen 30-second trials at 30-second intervals purports to 15 minutes of testing. This testing commenced two minutes after icing finished. It may be that significant physiological changes occurred over that time to restore homeostasis, potentially over-riding any cold-induced changes. Testing force variability whilst immersed in cold water may overcome this effect. Additionally, iced water immersion, whilst inducing temporary anaesthetisation — as seen by changes in 2-point discrimination — is extremely unpleasant when prolonged. Nocioceptor activity may have enhanced force control in the iced condition. It is

also likely that visual cues received as a component of the test protocol ablated any cold-induced deterioration of force control (Lowe, 1995). Tests of force variability before and after intervention without visual feedback would provide a much more reliable indication of the effect of cryotherapy on force control.

Gandevia and McCloskey (1977) investigated weight matching ability in healthy individuals before and after partial curarisation of the upper limb. Blindfolded healthy adults matched finger extension forces by pushing up against levers that elevated reference and comparison weights. Reference weights were 100g and 200g and comparison loads were altered by repositioning weights along the lever arm until subjects reported that the two weights felt equal. Gandevia and McCloskey stated that weight estimation deteriorated drastically as a result of curare infusion-induced paresis and that there was a gradual return to pre-curarisation matching levels as handgrip strength returned over a period of 30 minutes. Unfortunately, error values were not reported.

Both Gelfan and Carter (1967) and McCloskey et al. (1983) have conducted *in vivo* tests on exposed human muscle and tendon tissue in subjects undergoing hand surgery under local anaesthetic. In both experiments, the muscles and tendons were compressed and stretched while adjacent joints were immobilised. Gelfan and Carter demonstrated that subjects perceived neither pressure, stretch nor illusory movement during muscle deformation, and accordingly rejected the notion of 'muscle sense'. McCloskey et al. (1983) repeated the same experiment and reported that all subjects accurately detected stretch of their exposed tissues, a finding dissimilar to Gelfan and Carter. McCloskey's subjects commonly described the illusion of rotation at the joints to which the muscle attached when tendons were stretched, but did not report any 'sensations' of force or pressure.

In an attempt to further elucidate the systems responsible for generating perception of muscle force, a contralateral force matching protocol was undertaken by a subject with large fibre sensory neuropathy and seven healthy controls using grip dynamometers (Lafargue et al., 2003). De-afferented patients demonstrating large myelinated sensory neuron disruption are typically unresponsive to the peripheral mechanical stimuli needed to provide feedback

during motor tasks. Subjects performed bilateral palmer grips at reference forces of 10%, 30% and 50% MVC of the weakest hand. Subjects were asked to base matching on grip sensation (perception condition 1) or perceived effort (perception condition 2). The accuracy, precision and stability (ability to maintain force throughout the 9-second trial) of matching forces were compared between groups for both hand conditions. Whilst maximum grip force was significantly reduced in the de-afferented patient (L - 148N versus 252N and R - 167N versus 278N for de-afferented and control subjects respectively), subjects demonstrated significantly ($p<0.05$) similar levels of accuracy, precision and stability across force and perception conditions in all but the 10% MVC trials. The de-afferented subject reported experiencing neither fatigue nor awareness of generated force during any of the testing, demonstrating the absence of peripheral sensation. The de-afferented subject was able to perform all the testing in the absence of peripherally generated afferent input signifying that motor command was sufficient to enable the assessment and scaling of muscular forces. That the accuracy, precision and stability of grip tasks was substantially impaired at the 10% maximal grip level in a subject lacking proprioceptive awareness from peripheral receptors suggests that efferent motor output alone cannot encode force sensation at low levels of motor activity.

Raj et al. (1985) compared weight appreciation in subjects with chronic anaesthesia due to leprous neuropathy with that of healthy control subjects. Subjects with leprous neuropathy were sensitive to pain and vibration but insensitive to touch and pressure in a glove distribution extending above the wrist. Subjects with leprosy also demonstrated markedly reduced intrinsic hand muscle power but normal extrinsic hand muscle function. Weight estimation was assessed under three test conditions using lifting loads attached to the middle finger which ranged in weight from 20 to 500g. Weight estimation was tested in the absence of joint movement (passive condition), with isolated metacarpophalangeal flexion (finger movement condition), and with isolated elbow flexion (elbow movement condition). Subjects with leprous neuropathy were completely unable to detect weights up to 500g during the passive condition and were unable to consistently detect weights below 200g during the two movement conditions. Weber's fractions for the 200 and 500g weights were

0.12 and 0.10 versus 0.43 and 0.34 for the control versus leprosy groups during the finger flexion condition. Weight estimation in the elbow movement condition did not significantly differ at the higher test levels, with Weber's fractions of 0.26 versus 0.29 (200g) and 0.14 versus 0.18 (500g) obtained for the control versus leprous neuropathy subjects respectively. The inability of leprous subjects to detect weight in low load conditions both passively and actively confirmed the role of cutaneous receptors in force and weight appreciation at the hand. That patients with leprosy demonstrated improved weight discrimination at the 500g level during elbow flexion when compared to finger flexion is interesting when differences in proximal versus distal muscle innervation are considered. The fine muscles of the hand are almost entirely activated by monosynaptic corticospinal inputs whereas proximal musculature receives monosynaptic corticospinal input as well as activatory inputs from subcortical motor pathways (Kandel et al., 2000; Lüscher, Ruenzel, & Henneman, 1979; Williams et al., 1989a). The corollary discharges produced during proximal muscle activation are a fusion of efferent copies derived from multiple cortical and subcortical regions and as such may present the cortex with a more complex data set for force encoding. This supposition is supported by the fact that Weber's fractions during the elbow flexion condition had plateaued at 400g whilst a pattern of decreasing Weber's fractions for the finger flexion condition were still evident at the 500g level.

In the Gandevia and McCloskey (1977) study discussed above, weight matching tests were also conducted with a group of adults who had experienced a neurological injury or illness resulting in upper motor neuron weakness, but not sensory loss, in a single upper arm. A 400g Mercury-filled reference tennis ball was placed in one hand and subjects were instructed to find a tennis ball that matched the reference ball using their other hand. A subgroup of four subjects also performed the index finger extension task described previously, using a reference force of 100g. The authors reported that subjects chose balls heavier than the reference weight when the reference weight was held in the affected hand indicating that weights were judged to be heavier when lifted with the affected side. Additionally this effect was related to the extent of hemiparesis, with markedly lower Weber's fractions produced by subjects with lower overall weakness.

Based on the studies reviewed in this section it is difficult to say whether central or peripheral mechanisms predominate during force coding. Rather than one mechanism dominating force appreciation, it is likely that force appreciation arises from integration of both feedforward and feedback processes at localised and distant sites of the body (Stillman, 2002). Both mechanisms working together with afferent input continuously compared to efferent output to allow prompt correction of movement and the control and management of fatigue and perturbations is a notion increasingly supported in studies of force appreciation (Cafarelli, 1982; Hampson et al., 2001; Jones, 1989b; Stillman, 2002). That certain subcategories of force sensation appear to rely more on corollary discharge (weight appreciation, sense of effort) and others on peripheral receptor firing (pressure, friction) may also have contributed to the contrasting results of past studies (Gandevia et al., 1992; Stillman, 2002).

From the papers reviewed, it would appear likely that an individual has access to multiple streams of peripherally and centrally generated proprioceptive inputs from which a global 'force appreciation' is derived. It may be that in the presence of multiple proprioceptive inputs, a point of saturation occurs whereby further somatosensory information becomes redundant and effects no further improvement in proprioceptive acuity. Further to this concept is the notion that the loss of some somatosensory information — e.g. through nerve damage or neurological dysfunction — may not necessarily reduce force appreciation. This notion is supported by findings where, as loads increased (as in the Lafargue et al., 2003 study) or task demands gained complexity (as in the Raj et al., 1985 study), the force/weight matching ability demonstrated by neurologically impaired subjects improved.

2.3 Measuring force appreciation

This section describes a variety of approaches used to describe and measure aspects of force appreciation acuity. Discrimination thresholds, force (and weight) estimation and matching protocols, assessment of force control and measurements of perceived effort have each been used to quantify and compare force appreciation in humans.

Psychophysics is a branch of psychology concerned with investigating relationships between stimuli properties and the sensory and perceptual process these stimuli engender (Coran et al., 1994). The processes of detection, identification, discrimination and scaling are fundamental components of psychophysics, the science that attempts to explore the relationship between the magnitude and character of a physical stimulus and the magnitude and character of the sensation experienced in the mind (Coran et al., 1994).

Detection describes the process of becoming aware of the presence of a stimulus (e.g. 'I see a new object') whilst identification is the process of naming the stimulus (e.g. 'It is another block'). Discrimination is the process of determining differences between stimuli (e.g. 'It is bigger than the other block') and scaling is the process of identifying the stimuli magnitude (e.g. 'It is twice as big as the other block') (Coran et al., 1994).

The calculation of differential thresholds allows the comparison of sensory responsiveness within the components of a given system (e.g. quadriceps femoris muscle receptors versus biceps brachii muscle receptors); across conditions (e.g. unfatigued versus fatigued subjects) and across individuals. Differential thresholds are also commonly referred to as difference thresholds, discrimination thresholds or difference limen values (Wolfe et al., 2006). The word limen derives from the Latin *liminis* meaning threshold or doorway. They are invariably expressed in the units with which the sensory stimulus is expressed (e.g. decibels, degrees, Newtons).

Both absolute and differential threshold measures are used in psychophysics studies. 'Absolute threshold' describes the minimally effective stimulus that elicits a *detection* response in 50% of the trials. Conventionally the differential threshold is the minimally effective difference in stimulus that is identified as *different* 75% of the time (Chaplin, 1985). Differential threshold usage is the more common method, as individuals have a one in two chance of guessing a difference correctly with absolute threshold measures.

Although it is typically 75%, the proportion of correct responses needed to determine a differential threshold varies considerably in published literature.

The range of differential thresholds within a subject population increases substantially as this 'detection response rate' increases. Detection response rates (DRR) of 0.5 and 1.0 indicate that the stimulus has been correctly identified as 'different' in 50% and 100% of trials respectively. Unless detection response rates are explicitly stated, comparisons between studies are difficult due to the considerable variation in DRR used during discrimination studies.

Calculating discrimination thresholds is a method frequently used to assess force appreciation. Two psychophysical techniques commonly used in discrimination studies are the 'method of constant stimuli' and the 'method of limits' (Wolfe et al., 2006). These methodologies are used to assess the degree of difference between two stimuli such that the two stimuli can be judged as 'not the same' (Coran et al., 1994). Both methods are also used for detection studies, where unpaired stimuli of varying intensities are presented to a subject who indicates whether or not they have perceived anything (Coran et al., 1994).

In discrimination studies, the method of constant stimuli is characterised by the repeated presentation of paired stimuli. Trials consist of a constant reference stimulus that is paired with varying comparison stimuli. The intensity of the comparison stimulus is either less than, more than or equal to the intensity of the reference stimulus (Coran et al., 1994; Wolfe et al., 2006). In a well-designed method of constant stimuli study the order of presentation (reference versus comparison), the direction of difference (more or less or equal) and the degree of intensity difference (between reference and comparison) are randomised. Subjects rate the comparison stimuli as less (lighter, smaller, weaker) or more (heavier, bigger, stronger) intense than the reference stimulus (Coran et al., 1994). Analysis of the proportion of 'heavier' and 'lighter' responses produces a discrimination threshold. The comparison stimulus that is judged lighter than the reference stimuli in 50% of presentations and heavier in 50% of presentations is called the point-of-subjective-equality and therefore represents the stimulus intensity judged to be most like the reference stimuli (Coran et al., 1994).

In comparison to the method of constant stimuli, which entails random presentation of stimulus pairs, the method of limits (for discrimination)

systematically increases or decreases comparison stimulus intensity until a difference is correctly identified (Coran et al., 1994; Wolfe et al., 2006). Also called the just-noticeable-difference method, this methodology involves repeatedly presenting a reference stimulus along with a comparison stimulus which is increasing (or decreasing) in regular increments. The method of limits protocol commonly uses diverging stimuli, with subjects describing pairs as 'same' or 'different' until a difference is correctly identified. Converging stimuli can also be used to find the point where a subject can no longer identify a difference. Clinically this method is commonly used for vision tests where patients are asked to state whether their ability to see a letter on a wall chart is made 'better' or 'worse' as progressively stronger lenses are compared until no further improvement in visual acuity is gained. As for the method of constant stimuli, terms such as bigger/smaller, lighter/heavier may also be used. With the method of limits, the discrimination threshold can be expressed as a level of uncertainty or is derived from the closest comparison intensity (to the reference) at which a difference was correctly identified in a nominated percentage of trials (e.g. 50% of trials).

The term *sensory continuum* describes the range of stimuli detectable by a sensory system. For example, the range of hearing for a healthy young person is approximately 20 to 20,000Hz (Moller, 2000). Therefore the sensory continuum of the human auditory system ranges from a low of 20Hz to a high of 20,000Hz. Through the mid-range of a sensory continuum, the just-noticeable difference between any two similar stimuli is a constant fraction of the reference stimuli's magnitude — in effect, a larger increase in comparison stimuli intensity is required for a difference to be detected when the reference stimulus is large (Coran et al., 1994).

Another way to describe an individual's ability to discriminate between two stimuli is to calculate the 'interval of uncertainty' (Murase, Kinoshita, Ikuta, Kawai & Asami, 1996). An example of a recording sheet for a weight estimation task is given in Figure 2.1. In this fictional weight estimation task, the goal of the subject was to describe whether a comparison weight was heavier or lighter than the reference weight. The ticks and crosses in the figure represent correct and incorrect responses respectively. The interval of uncertainty in this example

describes the stimulus range falling between the differential thresholds for weights judged lighter than the reference and weights judged heavier than the reference. In this example, the differential threshold for lighter is calculated as 0.3kg and the differential threshold for heavier was 0.4kg. In this example the interval of uncertainty would be expressed as -0.3 to 0.4kg. The interval of uncertainty represents the point along the sensory continuum where chance rather than discriminative acuity dictates the response a subject makes. Repeated acquisition of 'levels of uncertainty' for varying reference values provides a measure of discrimination ability for a given sensory modality. Conventionally the differential threshold is derived by dividing the interval of uncertainty by two and allows a differential threshold value which has been averaged across the direction of the differences (Coran et al., 1994). A differential threshold derived this way can also be labelled a point-of-subjective-equality (Lafargue & Sirigu, 2002).

Example: Deviation from reference weight (kg)											
Round	-0.5	-0.4	-0.3	-0.2	-0.1	0.0	0.1	0.2	0.3	0.4	0.5
1	✓	✓	✓	✓	✗	✗	✗	✗	✓	✓	✓
2	✓	✓	✓	✗	✗	✗	✗	✓	✗	✓	✓
3	✓	✓	✗	✓	✗	✗	✗	✗	✓	✗	✓
4	✓	✓	✓	✗	✓	✗	✗	✗	✗	✓	✓
5	✓	✓	✓	✗	✗	✗	✗	✗	✓	✓	✓
6	✓	✓	✓	✓	✗	✗	✗	✓	✗	✓	✓
7	✓	✓	✓	✗	✓	✗	✗	✗	✗	✓	✓
8	✓	✓	✗	✓	✗	✗	✗	✗	✓	✗	✓
% correct	100	100	75	50	25	0	0	25	50	75	100
				←	Interval of uncertainty		→				

Figure 2.1. Interval of uncertainty

Regardless of the method used to determine discrimination ability for a given sensory modality, small differential thresholds and intervals of uncertainty represent higher sensory acuity. Whilst these techniques allow for comparison

between subjects within a given sensory modality, further treatment of the data is often undertaken.

Appreciating differences in sensory discrimination across modalities (e.g. light touch versus pressure) and between different sensory arrays (e.g. fingertip versus heel cutaneous receptors) is assisted by the use of Weber's fractions. The Weber's fraction is a measure of relative error (see Appendix 2) and can be obtained by dividing the differential threshold (in a discrimination protocol) or absolute error (in a matching protocol) by the reference value. As a proportion, the Weber's fraction becomes 'unit-less' allowing for comparisons between sensory modalities. In discrimination studies Weber's fractions represent the proportion by which a stimulus must be altered to enable an identifiable change (Coran et al., 1994). In 'matching' studies Weber's fractions express the degree of mismatch, proportional to the target stimulus occurring during testing.

This relationship between the differential threshold/absolute error and the magnitude of the reference stimuli is described by Weber's law:

Weber's law: $k = \dfrac{\Delta I}{I}$

(where k = constant (Weber's fraction), I = initial (reference) stimulus intensity & ΔI = differential threshold or absolute error) (Coran et al., 1994).

Although less reliable at inner and outer extremes of a sensory continuum, Weber's fractions have repeatedly been demonstrated to be reliable measures of the overall sensitivity of a sensory modality to difference (Coran et al., 1994; Jones, Hunter, & Irwin, 1992; Wheat, Salo, & Goodwin, 2004). Utilising Weber's law, detection thresholds have been determined for a large variety of proprioceptive functions (see Table 2.2).

The higher the perceptual complexity involved in detecting, identifying, discriminating and scaling a particular sensory modality, the higher the Weber's fraction will be for that modality (Gandevia & Kilbreath, 1990). High Weber's fractions indicate that a sensory modality is less responsive to detecting change. This may be demonstrated by considering the Weber's fractions for stiffness, force and movement. Stiffness (0.23) has a Weber's fractions three

times that of force (0.07) and movement (0.08) (Gandevia & Kilbreath, 1990). Jones and Hunter (1990) assessed differential thresholds for stiffness using a protocol whereby subjects performed concentric elbow flexion within an elbow splint such that resistance to movement of the splint could be altered. The authors suggest that the task required an awareness of both movement and force parameters which accounted for the higher Weber's fraction. As an individual becomes better able to detect, identify and scale a sensation, an individual's Weber's fraction will decrease (Mucha, 2002) as seen in a study by Waddington and colleagues (1999). Proprioceptive exercise by way of wobble board training significantly improved Weber's fractions for discrimination of inversion movements (0.09 to 0.06) in a group of elite rugby league players (Waddington, Adams, & Jones, 1999).

Table 2.2. Typical Weber's Fractions

Sensory modality	Weber's fraction	Source
Force	0.07	(Jones, 1989b)
Movement	0.08	(Jones et al., 1992)
Position	0.08	(Jones et al., 1992)
Elastic stiffness	0.08	(Nicholson & Adams, 2000)
Weight	0.10	(Brodie, 1985)
Viscous stiffness	0.15	(Nicholson & Adams, 2000)
Mass	0.16	(Ross & Brodie, 1987)
Tangential fingertip pressure	0.16	(Wheat et al., 2004)
Stiffness	0.23	(Jones & Hunter, 1990)
Viscosity	0.34	(Jones & Hunter, 1993)

Weber's fractions can produce misleading data when used to compare acuity at different force levels within an individual's force-generating capacity, an example being found in a study by Jones (1989b). When measuring force matching acuity across differing levels of submaximal force, the smallest Weber's fractions were produced at lowest force levels (15% and 25% MVC). However, the largest constant errors were also produced by these two levels; a

finding that highlights the risk of reporting matching errors in absolute terms (e.g. Newtons, grams) rather than expressing them as a percentage of target forces (% MVC). In the same way, additional scaling to the maximal capacity of the muscle producing the comparison force is needed during contralateral matching tasks. For Weber's fractions for force acuity to be useful, care must be taken to describe the joint position and submaximal force level at which testing was conducted. As stated in Appendix 2, a more useful measure may be the relative score (used by West, Smith, Lambert, Noakes & St Clair-Gibson, 2005), which reports directionality (under or overshooting the target) and is scaled to reference values.

Detection and discrimination tests are primarily passive in nature with subjects responding to imposed sensory stimuli, such as an auditory signal, an external weight or a visual cue. Another method of measuring the sensitivity of a sensory modality is to perform a task dependent on the sensation of interest. The degree of accuracy and precision demonstrated whilst performing the task can indicate the sensitivity of perception for that modality. Accuracy and precision are qualitative concepts described by quantitative measures including absolute errors, standard errors, standard deviation, root mean square errors and confidence intervals. Accuracy in force matching is a measure of the extent of agreement between target forces and the forces generated during testing (Williams et al., 1992). Precision can be described as the extent of agreement between accuracy measures over the duration of testing or across independent tests (Williams et al., 1992) (see Figure 2.2).

'Bias' and 'error' are common synonyms for the term accuracy. In a force matching example, if the force generated was 90g whilst trying to match a target of 100g, the subject could be said to demonstrate 90% accuracy or display a 10% bias or error. More specifically, the terms absolute error, relative error and percentage error are used to describe the discrepancy in real terms — absolute error equals 10g; relative to the target force — relative error is 0.10; and as a percentage of the target force — percentage error equals 10%. Error values describe the difference between the performance and target values and can be expressed as a positive or negative value (indicating whether the subject under or overshot their target); however this directionality is not routinely reported in

'matching' studies. Although commonly used in force matching studies involving paired force output tasks, accuracy measures can be derived from single isolated motor efforts (Jackson & Dishman, 2000; Jones, 1989a; West et al., 2005).

Rather than describing the relationship of a performed task to the target task, 'precision' describes how closely repeated measurement values are to each other (Williams et al., 1992). Repeatability and reproducibility are qualitative precision-based concepts. 'Repeatability' describes precision under similar test circumstances (e.g. same subject, same measuring technique, same measurer). 'Reproducibility' describes precision under different circumstances (e.g. same subject, same measuring technique, different measurers). It can be used within a trial (e.g. sustained muscle contraction) to measure output variation through the course of the trial. It can also be used to describe how effectively a subject can repeatedly produce a specific output between trials. Measurements can be very precise without being accurate in that a subject can under or over shoot a target value by the same amount repeatedly (see Figure 2.2, 'C'). Less commonly, subjects demonstrating poor precision can exhibit high levels of accuracy as mean performance values approach the target (see Figure 2.2, 'B'). The combined use of both accuracy and precision outcomes can be used to describe subject performance during repeated testing.
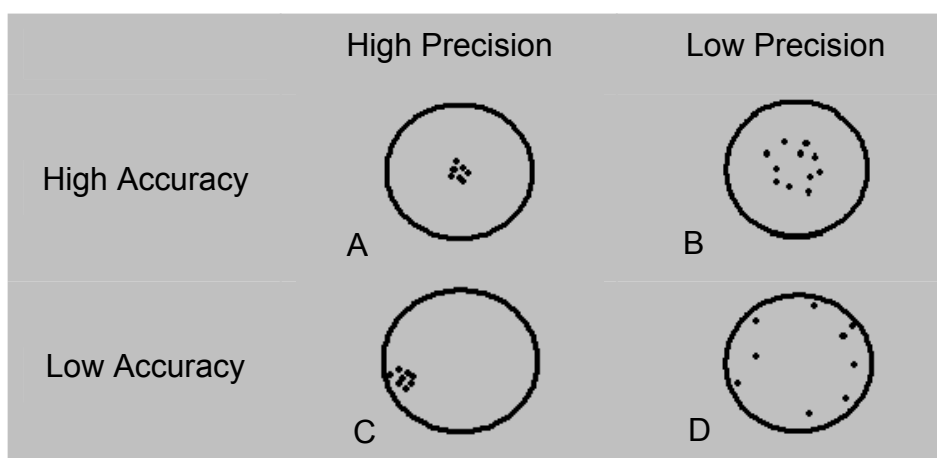

Figure 2.2. The relationship between accuracy and precision

Individual and group means and variance measures (e.g. standard deviation, standard error, confidence intervals) are used to quantify both accuracy and precision. There appears to be no consensus on which variance measure is the most valid or reliable for use in force appreciation studies.

Subjective measures of muscle exertion or effort have been used in force appreciation studies (Banister, 1979; Gandevia et al., 1993; Hampson et al., 2001). The most widely used measure of perceived exertion is the Borg Rating of Perceived Exertion Scale (Chen, Fan, & Moe, 2002). Both the 15-point Borg Scale and the 10-point Modified Borg Scale are well validated and reliable tools which allow subjects to rate the perceived effort of performing a task (Chen et al., 2002; Pincivero, Campy, & Coelho, 2003). Describing effort as a percentage of perceived maximal capacity is another strategy used by researchers to rate perceived exertion (Banister, 1979).

Assessment of perceived exertion has been used to gauge differences in force appreciation between muscle groups (Banister, 1979) and to describe changes in force appreciation resulting from interventions including muscle training and fatigue (Kellerman, Martin, & Davenport, 2000; McCloskey et al., 1974; Supinski, Clary, Bark & Kelson, 1987). Whilst Borg scales have been well validated as measures of perceived exertion (Borg, 1982; Chen et al., 2002), McCloskey and colleagues (1974) have shown that subjects readily confuse sense of localised muscle tension with sense of generalised effort. As such, use of perceived exertion scales may lack sufficient specificity when assessing force appreciation. That many perceived exertion scales are anchored by minimal and maximal ratings of perceived effort potentially effects a distortion in exertion ratings during times of very high or very low levels of motor output (Kellerman et al., 2000).

Banister (1979) attempted to model the relationship between physical effort and perceived exertion by considering differences in perceived effort across the force continuum (generated force ranging from zero force to maximal voluntary capacity) of the quadriceps femoris muscle and adductor pollicis muscles in healthy adults. Subjects performed cued submaximal contractions which they rated using both a modified Borg scale and by scoring contractions as a

percentage of their maximal effort. Banister reported that perception of effort changed according to muscle group, with adductor pollicis demonstrating a rapid increase of perceived force over a relatively small load when compared to the quadriceps femoris results. Unfortunately, Banister plotted perceived effort scores against muscle forces generated rather than as a function of maximal voluntary capacity. As a consequence, Banister's conclusion that the adductor pollicis muscle demonstrated relatively less discrimination in the sense of perceived effort between different exerted forces should be considered with caution. Banister also reported that the measure used to determine perceived effort had an influence on findings. Banister used a force constant (c) — defined as the applied force which subjects rated as 66% of their perceived maximum — to compare appreciation of effort between the muscle groups during muscle contractions. The force constants derived from Borg ratings were 1.6 and 1.8 times bigger than those derived from percentage-of-maximal-effort ratings for adductor pollicis and quadriceps femoris respectively. This difference between the effort measures suggests that the perceived exertion assessment tool used will influence the magnitude of exertion ratings.

Information on an individual's ability to rate their muscle forces may be gleaned from studies investigating weight appreciation. 'Weight appreciation' describes the ability to quantify weight and to differentiate between multiple weights (Brodie, 1989; Kilbreath & Gandevia, 1993). Weight appreciation studies commonly utilise discrimination, weight matching and/or weight estimation protocols (Brodie, 1988; Gandevia & Kilbreath, 1990; Ross & Brodie, 1987). As with force appreciation studies, discrimination thresholds and accuracy measures are frequently used to describe weight appreciation. Both force and weight matching tasks have very similar sensory needs as weight matching and/or estimation protocols almost invariably require subjects to actively lift or hold reference and comparison weights. Weight matching/estimation studies also frequently incorporate analyses of perceived effort and tension (Burgess & Jones, 1997; McCloskey et al., 1974). These similarities allow for utilisation of weight appreciation findings when considering human force appreciation. Some caution is warranted however as most weight appreciation studies require subjects to lift weights with their hands (Gandevia & Kilbreath, 1990; Gandevia & McCloskey, 1977; McCloskey et al., 1974; Raj et al., 1985; Ross & Brodie,

1987). Cutaneous receptors (that signal skin pressure and tangential shearing forces) play a significant part in sensory acuity during weight matching tasks (discussed in Section 2.2.2) and it is possible that weight estimation tasks rely more on cutaneous sensory input than force matching protocols (Kilbreath et al., 1997).

In summary, force appreciation can be assessed using a wide variety of testing strategies. To date, the ways of testing and labelling aspects of force appreciation have varied greatly such that gaining an understanding of force appreciation in humans is still difficult. Comparisons between groups and sensory modalities are considerably hindered by a lack of consensus on the means of expressing the size of detection and discrimination threshold and it is probable that the failure of many previous researchers to express target and comparison forces relative to maximal capacity reflects an inadequate awareness of force coding mechanisms.

The most common type of force appreciation methodology appears to be the force matching protocol utilising contralateral or ipsilateral tests. In ipsilateral and some contralateral matching methodologies, the comparison force is generated after the reference force. In most contralateral matching tests the two forces are generated concurrently.

In matching studies, subjects tend to produce comparison forces that require the same level of motor pool activation as that needed to generate the reference force (see Section 2.4). As a muscle fatigues, the level of motor pool activation required to perform a given task increases (Liu et al., 2003). Studies investigating fatigue and force matching have demonstrated that subjects produce excessive comparison forces with an unfatigued muscle when reproducing reference forces generated with a fatigued muscle (Cafarelli, 1988; Jones & Hunter, 1983). A benefit of serial matching tests is the ability to limit testing to the same muscle thereby minimising any fatigue effect because submaximal forces are being scaled to the 'same' maximum capacity. A disadvantage of the serial matching protocol is the need for test subjects to 'remember' the reference force and then reproduce it.

In contralateral matching protocols — that almost exclusively utilise concurrent reference and comparison force generation — subjects do not have to rely on a 'force memory' as reference and comparison forces can be compared in real time. To date there are no published reports of studies using both serial and simultaneous matching protocols to determine the importance and reliability of 'force memory'. A disadvantage of contralateral tests is the requirement of a 'healthy' control limb. When testing force appreciation in osteoarthritic subjects, a contralateral matching test would limit the pool of potential subjects to those with unilateral joint dysfunction only. Given that strength, force control and proprioceptive deficits have been found in the 'normal' leg of osteoarthritis subjects (Barrett, Cobb, & Bentley, 1991; Hall, Mockett, & Doherty, 2006; Hassan, Mockett, & Doherty, 2001; Koralewicz & Engh, 2000; Molloy, 2005; Sharma et al., 1997), contralateral force matching tests may not be appropriate.

Force and weight estimation protocols were less frequently used to assess force appreciation. As subjects only have a perceptual 'reference' for forces generated during estimation tests, West et al. (2005) contend that a 'sense of perceived effort' determines the magnitude of forces produced. In contrast, matching tasks, by their nature, supply individuals with an internal representation of the force required based on the efferent copy and sensory feedback produced from the previous 'reference' effort. It can therefore be argued that estimation tasks rely predominantly on feedforward force coding mechanisms whilst matching protocols investigate both feedforward and feedback contributions to force coding.

2.4 Force appreciation in humans

Force appreciation has been assessed at various sites in the human body including lower limbs, upper limbs, hands and mouth. Additionally, force appreciation studies have investigated the influence of force level, joint position, contraction type, age, training, pain, and dysfunction on the ability to accurately estimate, match and control forces. This section reviews current understandings of force appreciation in healthy and unhealthy human subjects.

2.4.1 Force appreciation using estimation studies

Force estimation strategies have improved understanding of force appreciation. Jackson and Dishman (2000) used accuracy and precision measures to assess perceived submaximal force production in healthy young adults (n=110) who performed bench presses at 25%, 50%, 75% and 100% of their maximum capacity. Accuracy was determined by comparing recorded submaximal outputs with the 'target' forces calculated from the maximal contractions performed. Precision was determined by the degree of variance within gender groups for the measures obtained at each level. Jackson and Dishman demonstrated a high correlation between perceived and target force production (male r=0.76 p<0.001; female r=0.75 p<0.001) across the four test loads. Relative scores of 1.15, 0.97 and 0.91 were obtained at bench press levels of 25%, 50% and 75% MVC respectively. Although group results pointed to reasonable accuracy when producing relative muscular forces, considerable variation in perceived submaximal force production amongst subjects was evident. The authors suggest the finding that healthy young adults in this study demonstrate considerable variation in the ability to produce target submaximal forces has potential significance for future research into force production and appreciation as well as rehabilitation studies. Detecting and matching subgroups of less accurate individuals within subject groups may facilitate better force appreciation research outcomes where interventions (e.g. fatigue, vibration) are studied (Jackson & Dishman, 2000). The authors also contend that poor force-producers with a tendency to overshoot may be at more risk of re-injury during rehabilitation whereas individuals that undershoot may delay their recovery by failing to sufficiently load the healing areas, both outcomes having the potential to influence research outcomes in rehabilitation studies (Jackson & Dishman, 2000).

West and colleagues (2005) used a similar force estimation protocol to investigate the ability of young adults to accurately produce submaximal force levels (25%, 50% and 75% MVC), guided by perceptual feelings of exertion, before and after fatiguing isometric exercise. In sitting, with the knee positioned at 60° flexion, healthy adults (n=30) performed isometric force estimation tests with their knee extensor muscle group. The following experimental conditions

were considered: non-fatigue (condition 1), fatigue induced by sustained 20% MVC contraction (condition 2), and fatigue induced by sustained 100% MVC contraction (condition 3), with subjects producing a single set of contractions at the four target levels for each condition. Subjects displayed most accuracy when estimating the 50% MVC target level and demonstrated a consistent pattern of overestimating the 25% MVC target and underestimating the 75% MVC target. Relative scores — extracted from reported data — for the non-fatigued condition were 1.36, 0.94 and 0.77 for the 25%, 50% and 75% targets. Relative scores for the two fatigued conditions were very similar at 1.56, 1.06 and 0.83 versus 1.48, 1.05 and 0.87 for conditions two and three respectively. West et al's results demonstrate that force estimation ability was not significantly impaired by muscle fatigue. Of interest, these authors also included a 'naïve' test where subjects produced force estimations of 25%, 50% and 75% MVC without first performing a maximal voluntary contraction. In this series of tests, subjects were most accurate at the 25% MVC level (RS= 1.00) and substantially underestimated the 50% MVC (RS= 0.78) and 75% MVC (RS=0.72) targets suggesting that force estimation is improved by perceptually anchoring target levels.

2.4.2 Force appreciation across differing muscle groups

To date, little data has been reported regarding differences in force appreciation between muscle groups. The next three studies show that an individual's ability to accurately match forces appears to be similar across muscle groups.

Gandevia and Kilbreath (1990) elected to assess weight matching acuity in proximal and distal upper limb muscles to ascertain whether force appreciation was more acute in the hand. Healthy adult subjects (n=16) undertook a series of four contralateral and simultaneous weight matching tasks using an intrinsic index finger muscle, an extrinsic thumb muscle, elbow flexor muscles and a composite task involving the whole upper limb. Using a method of limits test protocol, subjects matched reference weights (3% MVC versus 15% MVC) and comparison weights simultaneously. When comparison loads were expressed relative to reference loads, weight matching accuracy was similar across all muscle conditions and greatest during the 15% MVC trials. Precision was

highest in the elbow flexors followed by the composite task. Elbow flexor and composite task precision was significantly enhanced by use of heavier reference loads. Gandevia and Kilbreath proposed that the difference in precision across muscle groups reflected the fact that the elbow flexor and composite protocols utilised multiple muscles during task performance. This in turn provided the cortex with a greater volume of sensory information — from efferent copies and peripheral mechanoreceptors — for analysis.

Kilbreath and Gandevia (1993) investigated weight matching acuity of the intrinsic and extrinsic muscles acting on the thumb and index fingers of healthy subjects (n=12). Using a method of limits test protocol, subjects completed contralateral simultaneous weight matching tasks using reference weights, scaled to each muscle's maximum, ranging from 2.5% to 50% MVC. Kilbreath and Gandevia demonstrated that subjects consistently underestimated the heaviness of the reference weight at all loads in all four muscles. Accuracy and precision improved as reference weights increased and plateaued for most muscles at reference weights over 15% MVC. The extrinsic thumb muscle demonstrated the greatest matching accuracy and maintained a similar degree of accuracy across all test levels. When data was pooled for finger versus thumb, the thumb muscles demonstrated greater accuracy and precision in weight matching. When pooled for intrinsic versus extrinsic groups, the intrinsic muscles were less accurate but more precise than their extrinsic counterparts when performing weight matching tasks.

Dover and Powers (2003) investigated the reliability of proprioceptive measures during internal and external rotation at the shoulder joint in healthy adults. Force reproduction accuracy was assessed in healthy subjects (n=31). In standing with arms abducted to 90º, subjects performed a reference contraction of 50% MVC using visual feedback. After three seconds a comparison contraction was performed without visual feedback. Extrapolated Weber's fractions of 0.13 and 0.13 for internal and external rotators respectively indicated no difference in force reproduction acuity between muscle groups. These results are approximately twice the Weber's fraction for force of 0.07 found by Jones (1989b), a result that may reflect the use by Dover and Powers of a relatively less stable and arguably less comfortable test position.

2.4.3 Force appreciation across differing force levels and joint position

It has also been shown that an individual's force matching acuity changes depending on the joint position and force level used for testing (Cafarelli & Bigland-Ritchie, 1979; Jones, 1989b; Weerakkody et al., 2003b).

Using a contralateral limb matching task Jones (1989) examined the effect of force levels on matching acuity. Subjects (n=14) performed paired isometric biceps brachii contractions ranging from 15–85% of their right maximum voluntary contraction. Findings were similar across gender and age groupings. Jones demonstrated that force matching was consistently overestimated at targets below 50% MVC, with marked underestimation of forces evident at the two highest target levels (75% and 85% MVC). When comparison forces were expressed relative to the comparison biceps brachii's MVC, it revealed that subjects were matching the proportion of MVC utilised by the reference biceps brachii rather than the absolute reference load generated. This finding suggested that, perceptually, the human cortex scales muscle force relatively rather than in gross physical units and further reinforces the role of cortically generated efferent copy in force appreciation.

These results have interesting implications for subjects who have experienced injury or muscle atrophy. Does the natural tendency to match relative forces conflict with the need to produce absolute force matches during manual tasks in individuals after injury? After an injury, a motor task utilising 50% of pre-injury MVC may utilise 75% of the post-injury MVC. If the acquisition of motor tasks involves encoding force production parameters relative to maximum capacity, an individual's reliance on a motor skill's force engram could result in inadequate force generation potentially causing microtrauma in local soft tissues and perhaps predisposing the individual to further injury. Alternatively, in a condition such as osteoarthritis, it might be advantageous to the management of loading on damaged articular cartilage.

The relationship between a muscle's length and its isometric tension generating capacity is a function of the degree of overlap between its actin and myosin filaments such that force generating capacity is reduced at shorter and longer

muscle lengths (Gordon, Huxley & Julian, 1966). The selective increase or decrease in the number of actin-myosin cross-bridges within muscle fibres ensures that this 'length-tension relationship' is maintained after injury, immobilisation, training and changes in tasks demands (Hortobagyi et al., 2000; Swynghedauw, 1986). The influence of changing muscle length on force appreciation acuity has been investigated in the next two studies.

Cafarelli and Bigland-Ritchie (1979) investigated the influence of muscle length on force matching acuity. Subjects (n=5) performed matching tasks using their adductor pollicis muscle. Three matching conditions were tested: matching with equal muscle length, with the reference muscle longer than the comparison muscle, and with the reference muscle shorter than the comparison muscle. Tests were conducted at a variety of submaximal force levels, but neither force level nor joint angles were reported. The findings demonstrated that force acuity changed as a function of the length–tension relationship in a muscle. When the reference muscle was placed in a shortened position, subjects produced comparison forces 108.3% higher than reference forces (RS=1.08). A lengthened reference muscle produced comparison forces that were 69.4% lower than required (RS=0.69). As the maximum tension-producing capacity of a muscle is influenced by muscle fibre length (McHugh & Tetro, 2003), these findings support the hypothesis that force sensation arises from efferent copy of motor activity rather than peripheral proprioceptors. The amount of force generated by a given number of shortened or lengthened muscle fibres is smaller than that produced by the same muscle fibres in 'mid-range' (Cafarelli & Bigland-Ritchie, 1979; Croce & Miller, 2006; McHugh & Tetro, 2003). If force coding relied solely on peripheral mechanoreceptors responding to changes in muscle tension, the matching errors produced in a contralateral force matching task such as that used by Cafarelli and Bigland-Ritchie would be unaffected by joint position and would be similar to those demonstrated by Jones (1989b).

Weerakkody et al. (2003b) investigated the influence of joint angle and length–tension relationship on torque matching at the elbow joint in healthy subjects (n=8). Subjects matched isometric flexion torque in the 'comparison' elbow joint, fixed at 90˚ flexion, to that produced in the 'reference' elbow, positioned in various degrees of flexion (5% and 20% MVC at 30˚, 60˚, 90˚, 110˚ and 120˚

elbow flexion). Subjects were instructed to match 'torque' not 'effort'. Torque–angle relationships were charted and optimum angles for maximum torque production were obtained for each subject. Subjects consistently and significantly ($p<0.05$) overestimated matching forces when reference arms were at angles above or below 60–90° elbow flexion. The size of the error for a given angle was larger for the 20% maximum condition for all angles. The optimum angle for maximum torque production approximated 90° of elbow flexion with a length–tension relationship showing significant ($p<0.05$) reductions in peak torque production as joint angles diverged from the 90° flexion point. Therefore a higher activation rate is required to achieve a target load at shortened and lengthened muscle lengths. Subjects produced the largest matching errors at the 30° and 120° joint angles, providing further evidence that the appreciation of torque is centrally generated based on efferent output.

2.4.4 Force appreciation studies involving the hand

Studies investigating force appreciation in muscle groups of the hand and in a variety of gripping tasks have been published using a variety of methodologies including force matching tasks, discerning discrimination thresholds and evaluating consistency during sustained exertions. As a result, much has been learnt about the influence of cutaneous sensation, load characteristics, handedness and task demands on acuity of force appreciation.

Unlike force appreciation in large muscles of the arm and leg, discrimination of force magnitude in the hand may rely more heavily on the input of cutaneous mechanoreceptors. To observe the role of cutaneous receptors on weight estimation ability, Gandevia and Kilbreath (1990, discussed above) also investigated weight matching acuity as an artefact of the width of tape used to support the weights at the first dorsal interosseous. Altering force displacement over the index finger by varying tape width during weight matching tasks did not improve accuracy or precision despite the index finger having higher tactile acuity than the other areas tested. This finding supported the role of efferent copy to encode muscle force, as variations in peripheral sensor outputs did not improve accuracy or precision.

*G*rip safety margin describes the difference between load force and grip force during a gripping task and is typically expressed as a percentage (Westling & Johansson, 1984). Grip safety margins generally decrease in size as load forces increase. Westling and Johansson (1984) and Monzee et al. (2003) both established that digital anaesthetisation significantly increased grip safety margin sizes during grip tasks thereby indicating that sensory feedback from cutaneous finger receptors was important for the performance of gripping tasks. Even when subjects were well acquainted with the task to be performed, grip safety margins were much higher after anaesthetic (Monzee et al., 2003). Both Westling and Johansson (1984) and Monzee et al. (2003) have suggested that cutaneous mechanoreceptors signalled the source and direction of pressure applied to the skin and have postulated that this information was vital to optimal performance of gripping tasks. Monzee et al. (2003) also assessed the impact of grip surface characteristics on grip safety margins. Grip safety margins were significantly higher when subjects were gripping steel load plates compared to emery-covered load plates before and after anaesthetisation.

In addition to these two studies, Augurelle, Smith, Lejeune & Thonnard (2003) demonstrated that the ability to maintain a steady grip over time was impaired after digital anaesthetisation. Subjects were asked to lift and hold a 250g cylinder stationary for 20 seconds (static phase) and perform vertical oscillatory movements for 30 seconds (dynamic phase). On average, grip safety margins after anaesthetisation were more than double those obtained when skin sensation was intact. There was a significantly greater decline in grip force over the 20-second test period in the anaesthetised condition compared to the intact condition and in the dynamic phase of testing: 70% of subjects dropped their cylinder at least once, with drops or significant slips occurring in 48% of trials after anaesthetisation. Given the force decline and cylinder drop rate apparent after anaesthetisation it appears — in tasks involving the hand — that the cortex relies on cutaneous sensory input rather than the central and peripheral mechanisms coding the forces required to perform the grip tasks.

The results from these three studies confirm that cutaneous receptors perform a significant role in force control during activities involving the hand. There is no published data regarding the role of cutaneous receptors in force estimation or

control in other areas of the body. Additionally, the Monzee et al. (2003) results suggest that load characteristics also influence force control.

Manual asymmetry has been demonstrated in weight matching tasks (Brodie, 1988; 1989). In a 1988 study, Brodie measured differential thresholds of healthy adults (n=66) using unilateral consecutive paired lifts (left hand versus right hand) and bilateral simultaneous paired lifts (left hand first versus right hand first) with two presentation orders (lighter weight first versus lighter weight second). Hand preference did not affect an individual's weight matching ability for unilateral lifting; however, as a group, left-hand-dominant subjects, regardless of gender, performed significantly better than their right-handed counterparts (p<0.05) in the bilateral lift condition. Female subjects, regardless of hand preference, performed better with their right hands, whilst all male subjects performed best with their left hands. A constant error was detected in the bilateral lift condition in which subjects reported weights felt heavier in one hand. Regardless of gender, handedness or hand used, difference limens were lower when the lighter weight was presented first indicating that order of presentation of weights influenced results. Whilst the influence of hand preference on force matching acuity has not been reported to date, the findings of Brodie suggest that control and subject groups ought to be matched for handedness when employing bilateral matching methodologies.

Force appreciation acuity has been shown to differ as a function of the specific demands of a task. Lateral and fingertip pinch force discrimination were assessed in healthy subjects by Williams et al. (1991). Healthy female subjects (n=24) performed a series of paired comparison tests for a fingertip pinch condition and a lateral pinch condition. A method-of-limits protocol was employed to determine differential thresholds. The study used reference values equating to 10, 25, 50 and 75% of established normative maximum grip strength (nMVC) for fingertip and lateral grip for the dominant hand of adult females. Differential thresholds differed significantly (p<0.05) between grip conditions. At 10% nMVC, a 50% increase in comparison load was required before a difference was registered with a fingertip pinch, compared with a 100% increase for the lateral pinch task. The differential thresholds at 25% nMVC were similar with a near 20% increase required by both pinch conditions. At

75% nMVC, a 13% increase in comparison load was required with a fingertip pinch, compared with a 7% increase for the lateral pinch task.

Pang, Tan, and Durlach (1991) investigated the influence of force, distance, finger span, velocity, and technique on force discrimination during active finger motion. Five subjects performed fingertip grips which varied in reference force, finger span, squeeze distance, squeeze velocity and mode of test termination (sudden block versus sudden release). Consistent discrimination thresholds were recorded with a just noticeable difference of 7% (Weber's fraction 0.07) of the reference regardless of experimental condition. The finding that changes in reference force did not affect discrimination threshold is at odds with other force discrimination studies.

The repeatability of hand grip force production was examined in 12 healthy right-hand-dominant adults (Lowe, 1995). Lowe hypothesised that varying the number of sequential force exertions would influence the accuracy of force reproduction with complex sequences demonstrating greater variance than simple ones. Using a grip dynamometer subjects performed force matching tasks at submaximal levels of 20%, 35%, 50% and 65% MVC. Subjects had to reproduce multiple reference grips, matching both sequence and grip intensity. In the simple condition, the reference forces were paired according to load to produce light (20% and 35% MVC) and heavy (50% and 65% MVC) blocks. In the complex condition, subjects performed all four reference levels in a randomly presented order. Lowe reported that force matching accuracy increased as reference loads increased; however, there was no significant difference ($p<0.05$) in force matching acuity between the simple and complex conditions.

Somodi, Robin, and Luschei (1995) used a magnitude estimation procedure to determine the accuracy and reliability of sense of effort in the oral motor system and hands of healthy adults. Healthy adults (n=20) performed tongue compressions and palmer grips at target levels between 10% and 100% maximum capacity. Subjects consistently overestimated the low targets and underestimated the high targets. Pressures generated during performance of the lowest submaximal targets resulted in higher ratings of perceived exertion

for the hand when compared to those for the tongue. Between 30% and 60% maximum pressure, response curves flattened indicating that perceived effort increased more rapidly for a given increase in generated pressure through that part of the force continuum. In the hand, lower levels of pressure were generated for given levels of perceived effort. To explain this phenomenon, the authors proposed that fine motor tasks performed by the hand required a greater portion of the motor neuron pool than fine motor tasks of the tongue. While the assessment of force appreciation in the hand is relatively easy given the profusion of grip dynamometers in clinical settings, the usefulness of comparing force appreciation in gross muscles groups to that of the hand during gripping tasks may be diminished if the particular functional demands of the human hand influence force appreciation across the force continuum.

In all, the studies involving force appreciation in the hand demonstrate a significant reliance on cutaneous mechanoreceptors when attempting to match forces or lift weights and that the pattern of overestimation of lower forces and underestimation of higher forces was evident during grip tasks.

2.4.5 Force appreciation studies involving the mouth

Force appreciation studies involving the mouth and lips have provided some insight into the relative importance of muscle versus joint receptors to bite force discrimination. Bite and lip compression force discrimination appears to be similar to that produced by studies testing upper and lower limb force acuity. Previous investigation of bite and lip force discrimination has shown that accuracy in force production deteriorates at the extremes of the force continuum (Williams et al., 1984a; Williams, Coffey, Turner, Crary, Capen & Wharton, 1992; Williams, Vaughn, & Cornell, 1988). Additionally bite force appreciation has been shown to deteriorate in the presence of sensory and mechanical dysfunction (Williams et al., 1984b; Williams et al., 1989b; Williams, Levin, La Pointe et al., 1985; Williams et al., 1987). A number of studies have attempted to discern whether efferent output, joint and muscle receptors or other mechanoreceptors mediate bite force appreciation in the mouth.

Sensory receptors within the periodontal ligament, temporomandibular joint receptors and mechanoreceptors in the muscles of mastication are three systems proposed to mediate bite force discrimination (Williams et al., 1984b). In an endeavour to ascertain the respective importance of each system, Williams et al. (1984b) used selected anaesthetisation to create four experimental conditions: control, incisor block, temporomandibular joint block, incisor & temporomandibular joint block. Twelve adults performed the bite force matching tasks using a range of reference loads (500g–3000g). Bite force discrimination was decreased for both conditions involving incisor anaesthetisation. The temporomandibular joint block in isolation did not affect bite force discrimination, demonstrating that the periodontal ligament (which invests and supports the teeth) is significantly more sensitive to isometric bite loads than the temporomandibular joint mechanoreceptors. This finding was reinforced by Williams, Henry, and Mahan (1989b) who demonstrated no significant difference in bite force acuity after bilateral anaesthetisation of joint mechanoreceptors at the temporomandibular joints.

2.4.6 Force appreciation across differing age groups

Differences in force accuracy and steadiness have been found in older subject groups. Hortobágyi and colleagues (2001) investigated quadriceps force accuracy and steadiness in older adults (n=27) versus young adults (n=10) before and after high or low intensity strength training. Subjects performed isometric, isokinetic concentric and isokinetic eccentric contractions over five second durations at a target load of 25N. Subjects were instructed to match and sustain target levels as smoothly and steadily as possible. Older adults demonstrated 190%, 50% and 80% greater error in matching the 25N target than younger adults for isometric, concentric and eccentric contractions respectively. Older adults demonstrated 150%, 0% and 60% (isometric, concentric and eccentric) less force steadiness than their younger counterparts. Force training at both intensities was equally effective in improving force accuracy in older adults by 32% and 31% respectively for concentric and eccentric isokinetic contractions. Force steadiness improved by 20% and 40% respectively. Interestingly, strength training did not produce any significant (p>0.05) improvement in accuracy or steadiness during isometric contractions.

Additionally, there was no improvement in accuracy or steadiness in the younger control group. Accuracy and steadiness was markedly better during the isometric condition when compared to the isokinetic conditions.

Schiffman and colleagues (2002) investigated the effects of age and feedback on the performance of sustained submaximal isometric knee extensions in an attempt to assess whether normal ageing affected force control. Healthy younger (n=20, $\bar{x}$ age 25.8 years) and older (n=20, $\bar{x}$ age 71.8 years) adults performed isometric knee extensions at target loads of 20% and 60% MVC with and without visual feedback. Based upon graphs presented in this paper, accuracy levels of 95% and 100% (with and without sustained visual feedback) versus 93% and 88% were obtained from older versus younger subjects at the 20% maximal capacity level. At the 60% maximal capacity level accuracy levels were 96% and 83% versus 97% and 88% respectively. Force variability, when expressed relative to submaximal capacity, was similar for both groups at both levels (3.8 versus 2.8 and 3.2 versus 3.4 at 20% and 60% maximal capacity for young versus old subjects respectively) regardless of feedback condition. From these results it appears that variations in force accuracy and steadiness exist between older and younger adults, dependent on the level of submaximal force produced. It is possible that this reflects differences in central versus peripheral contributions to force encoding.

The Hortobágyi et al. (2001) and Schiffman et al. (2002) studies both demonstrated force control deficits in older versus younger subjects; a factor of significance considering that individuals awaiting knee joint replacement surgery — the major inclusion criteria for the osteoarthritis subjects recruited for this research project — are generally aged over 60 years.

2.4.7 Force appreciation and pain and dysfunction

Hortobágyi and colleagues (2004) investigated quadriceps force accuracy and steadiness in patients with osteoarthritis of the knee (n=20 versus healthy peers n=20). Subjects performed isometric, isokinetic concentric and isokinetic eccentric contractions over 5-second durations at target loads of 50N and 100N. Subjects were instructed to match and sustain target levels as smoothly and

steadily as possible. Accuracy and steadiness was markedly better during the isometric condition when compared to the isokinetic conditions for both subject groups. Osteoarthritis subjects demonstrated significantly ($p<0.05$) less accuracy and steadiness than their healthy peers at both force levels for both isokinetic contraction conditions. There was no demonstrated difference between groups for the isometric condition. The authors found that error and variation was greater in more extended knee positions, a finding which they attributed to three possible mechanisms: reduced sensitivity of knee joint proprioceptors in the osteoarthritis group, Type Ia sensory fibre disadvantage due to the quadriceps muscle being at a short length, and a reduced effectiveness of reciprocal inhibition mechanisms in osteoarthritis subjects.

Brockett, Warren, Gregory, Morgan and Proske (1997) investigated force appreciation after performance of eccentric and concentric exercise in human elbow flexors. Force appreciation was assessed using a contralateral force matching protocol with a reference load of 10% MVC. For each subject (n=9), arms were randomly assigned to perform 20–35 minutes of repeated concentric or eccentric contractions of the elbow flexors at 20% MVC (minimum 120 contractions). Eccentric exercise produced significant ($p<0.05$) muscle tenderness and loss of strength consistent with eccentric-exercise-induced muscle injury. Subjects overshot the target when using the 'injured' muscle to generate the reference load and undershot the target when the injured muscle was used to generate the comparison load. The direction of these errors suggested that subjects perceived a greater force output from the injured muscle. The authors suggested that changes in force sense occurred because peripheral receptors were responding to alterations in intramuscular length and tension after exercise-induced injury. The duration of these changes (less than 96 hours) supported the notion that exercise-induced muscle damage rather than fatigue and metabolite accumulation was responsible for the changes seen. The authors suggested that altered resting muscle tension (evidenced by changes in resting elbow angles) may have activated more tendon organs giving rise to perceptions of higher force production; that eccentric exercise may have caused damage to both intra- and extrafusal muscle fibres; and that muscle spindles may have been mechanically unloaded by damage-induced contractures such that receptor sensitivity was affected.

Weerakkody et al. (2003a) attempted to differentiate between the effect of pain and that of induced weakness on force appreciation after the induction of muscle soreness by hypertonic saline injection. Subjects (n=5) performed bilateral force matching tasks with the elbow joint positioned at 90° flexion with a reference level of 30% MVC. Pain was perceived within 30 seconds after injection, pain persisted for five–seven minutes, and at peak intensity was typically rated 3 to 4 on an 11-point visual analog scale. Subjects performed matching tests firstly with injection of the reference side, then (once pain had subsided) injection of the comparison arm. After the hypertonic saline injections, subjects consistently overestimated torques when the reference arm was sore, and underestimated torques when the comparison arm was sore. The size of errors decreased as pain subsided. Maximal voluntary capacity was not significantly influenced by hypertonic saline injection indicating that peak muscle function was not impaired by the noxious stimuli. The authors proposed that the noxious stimuli activated group III and IV muscle afferents which led to a reduction in motor cortex excitability. This in turn resulted in a mismatch between centrally generated effort and motor output thus producing matching errors.

Impaired lumbar position sense and poor postural control has been observed in subjects with chronic low back pain (Brumagne, Cordo, Lysens, Verschueren & Swinnen, 2000; Descarreaux, Blouin, & Teasdale, 2004; Leinonen et al., 2003; Mientjes & Frank, 1999). To ascertain whether low back pain also affects force appreciation, Descarreaux et al. (2004) compared force accuracy and force precision of low back muscles in healthy (n=15) versus chronic low back pain subjects (n=16). Using visual and verbal feedback, subjects were trained to accurately produce rapid isometric forces in a neutral standing position in each of the four experimental conditions (50% and 75% of maximal flexion and extension isometric force). Post training, subjects were tested without visual feedback during which time absolute error and variability data was collected. Descarreaux et al. reported that force accuracy and precision were similar in the control and low back pain groups; however, different motor strategies were employed by subjects with chronic low back pain. A subgroup of the chronic low back pain subjects (n=9) demonstrated a significantly (p<0.05) longer time to reach peak force. The authors suggested that this subgroup placed a greater

reliance on afferent feedback from muscle and joint receptors in a motor strategy designed to control and limit pain. The success of their chosen strategy was supported by the fact that this subgroup reported less pain during testing.

2.4.8 Force appreciation and vibration

The tonic vibration reflex is a spinal reflex induced when a muscle or tendon is vibrated resulting in muscle spindle firing. When an actively contracting muscle is vibrated, additional tension is generated via the tonic vibration reflex. The rate of Ia fibre discharge is proportional to the frequency and amplitude of vibration applied. Muscle spindle firing occurs in the absence of any cortical drive; therefore any changes in force acuity occurring as a result of applied vibration can be attributed to the activity of peripheral mechanoreceptor activity. In an attempt to demonstrate the effect of vibration on force matching acuity, healthy subjects (n=5) underwent a contralateral isometric force matching protocol to investigate force production in the quadriceps after muscle vibration (Cafarelli & Kostka, 1981). Vibration was applied to the patellar tendon. When the reference leg was vibrated, subjects overshot the target with their comparison leg because vibration induced the illusion of greater force production. This effect was also apparent in the opposite condition where vibrated comparison muscles produced less matching force due to the vibration-induced force illusion. Surface EMG readings confirmed that antagonist muscles remained inactive and therefore the tonic vibration reflex was isolated to the quadriceps muscle. These findings do not contradict the pre-eminence of centrally derived force encoding; rather they confirm that peripheral mechanoreceptors do play a role in the encoding of force sensation, as force encoded by efferent output alone would be unaffected by vibratory stimuli. It is likely that when both processes are equally active, central cues are predominant (Cafarelli & Layton-Wood, 1986).

2.5 Summary

From the literature review conducted, the following conclusions can be made about human force appreciation.

In force matching tasks, low forces/weights are typically overestimated and high forces/weights are typically underestimated, with matching acuity peaking when the underlying joint is in midrange and reference forces are between 30% and 60% of MVC.

A variety of peripheral mechanoreceptors and multiple cortical regions contribute to the coding of muscle forces. Pain, fatigue, and vibration interventions highlight the eminence of centrally generated force encoding. Whilst force matching at higher levels is possible in the absence of peripheral mechanoreceptor activity, central coding processes (motor efferent copies) are augmented by peripheral mechanoreceptor inputs at low levels of motor activation to enhance force coding acuity. An individual codes the magnitude of muscle forces relative to 'real time' maximal capacity.

Force control and matching is reduced in younger and older populations and pain, fatigue and dysfunction result in impaired force appreciation. Finally, cutaneous mechanoreceptors are especially important for grip matching tasks, and task complexity influences the relative contribution of feedforward and feedback mechanisms to force coding.

3. METHODOLOGY

This section includes an outline of subject recruitment strategies, the pain and function questionnaires utilised, a description of the experimental procedures including equipment used and instruction given, and a final section outlining data reduction strategies and the statistical analyses conducted.

3.1 Selection of subjects

Based upon reliability testing of the primary dependant variable and the work of Hortobargyi et al. (2004), a total of 40 subjects were required for attaining a moderate effect size with the alpha level at 0.05 and the beta level at 0.8.

3.1.1 Subjects with healthy knee joints

Subjects with healthy knees were recruited via advertising in the free local weekly newspaper. The advertisement solicited assistance from healthy adults older than 50 years with no history of arthritis in any lower limb joint. Interested subjects were contacted and given an initial telephone screening which surveyed the following criteria.

Inclusion criteria:
- Two healthy lower limbs

Exclusion criteria:
- Any history of significant knee injury or lower limb arthritis
- Any significant history of knee pain
- Any medical condition that would place the subject at risk during maximal and submaximal work levels (e.g. unstable angina, long-term steroid use)
- Visual or auditory dysfunction that might impair safety or the ability to perform the test tasks
- Neurological conditions (e.g. cerebrovascular accident, Parkinson's disease)
- Severe cognitive dysfunction
- Recent physiotherapy (within the last three months for any condition)
- Inability to provide informed consent.

3.1.2 Subjects with osteoarthritis of the knee joint

Subjects with osteoarthritis were recruited via orthopaedic outpatient clinics at Whangarei Public Hospital. Subjects on the waiting list for primary arthrodesis of the knee joint were contacted by mail and asked if they wished to be considered for inclusion in the study. Subjects wishing to be included were screened by review of medical files in the first instance and by telephone in the second instance. The following inclusion and exclusion criteria were applied.

The Whangarei Hospital Orthopaedic Department uses the New Zealand Health Funding Authority's 'CPAC' (clinical priority assessment criteria) tool to assign a priority ranking score (5–100) and clinical score (1–5) for patients awaiting a primary knee joint arthroplasty (see Table 3.1 and Appendix 3) (I Peters, personal communication, May 2006). At Whangarei Public Hospital, a minimum clinical score of '3' is required for placement on elective surgery waiting lists for knee arthroplasty. The large majority of patients awaiting knee replacement surgery at the time of this study were rated as '4' using the CPAC tool (I Peters, personal communication, May 2006).

Table 3.1. Priority criteria for access to knee joint replacement surgery at Whangarei Public Hospital

(New Zealand Ministry of Health, 2007; I Peters, personal communication, May 2006)

Criteria	Score				
CPAC priority score (5–100)	40	52	65	77	90
Clinical score	1	2	3	4	5
Accepted onto elective surgery waiting list			✓	✓	✓

Inclusion criteria:

- Osteoarthritis of a knee joint severe with a clinical score of 3 or higher using the CPAC tool (see Table 3.1 and Appendix 3).

Exclusion criteria:

- Any history of rheumatoid arthritis or other inflammatory illness
- Any history of joint replacement in the test knee or ipsilateral hip joint
- Any medical condition that would place the subject at risk during maximal and submaximal work levels (e.g. unstable angina, long-term steroid use)
- Visual or auditory dysfunction that might impair safety or the ability to perform the test tasks
- Neurological conditions (e.g. cerebrovascular accident, Parkinson's disease)
- Severe cognitive dysfunction
- Recent physiotherapy (within the last three months for any condition)
- Inability to provide informed consent.

Where possible, subjects with osteoarthritis of the right knee were chosen. After confirmation of suitability a subject received an information pack including an appointment time for testing, detailed information regarding the experimental format (including aims, rationale, methodology, potential risks and potential benefits of the study, see Appendix 4) and pain and function questionnaires. Subjects were encouraged during the phone call and in the letter to ask questions and were assured on repeated occasions that they could withdraw from the experiment at any stage without fear of repercussions.

A revised Physical Activity Readiness Questionnaire (PARQ) (Cardinal, Esters, & Cardinal, 1996) was included with the information pack and was completed prior to the test session. A minor modification was made to the question regarding bone and joint problems (see Appendix 5). Subjects were instructed to immediately review this questionnaire on receipt of their appointment letter, and if answering positively to any question were instructed to seek advice from their general practitioner regarding suitability for participation.

A general health screening questionnaire was devised for this study and administered as a final check prior to the commencement of testing (see Appendix 6). Questions screened for the inclusion and exclusion criteria listed above and for lower limb skin integrity.

3.2 Pain and function questionnaires

The following questionnaires were used to determine health status and baseline pain and function levels for the control and subject groups: the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC); the Community Healthy Activities Model Program for Seniors Physical Activity Questionnaire (CHAMPS); the Lower Limb Task Questionnaire (LLTQ); the Physical Activity Readiness Questionnaire (PARQ) and a general health screening questionnaire.

The lower limb task questionnaire assessing pain, stiffness and disability in the knee joint using a battery of 24 questions presented in a 5-point Likert format (see Appendix 7). The WOMAC index is a valid and reliable measure of pain and dysfunction in subjects with knee osteoarthritis (Barker, Lamb, Toye, Jackson & Barrington, 2004; Bellamy, 2002; Bellamy, Buchanan, Goldsmith, Campbell & Stitt, 1988). Within the WOMAC three subscales assess for pain (5 questions), stiffness (2 questions), and functional difficulty (17 questions). Likert responses of *none*, *mild*, *moderate*, *severe* and *extreme* are scored from 0–4 respectively. WOMAC scores range from 0 (no dysfunction) to 96 (maximum dysfunction).

The CHAMPS physical activity questionnaire for older people is a valid and reliable self-report physical activity questionnaire for older men and women (Cyarto, Marshall, Dickinson & Brown, 2006; Harada, Chiu, King & Stewart, 2001; Stewart et al., 2001a. See Appendix 8). It contains 41 questions through which subjects record average weekly activity participation, including frequency and duration, for a variety of activities performed within the last four weeks. Regarding light- and moderate-intensity physical activities, the CHAMPS questionnaire provides a measure of caloric expenditure and accumulated activity per week (Stewart et al., 2001b). The CHAMPS questionnaire utilises metabolic equivalent values (MET) that are adjusted for use with older adults (Stewart et al., 2001a). Metabolic equivalent values represent the ratio of work metabolic rate to standard resting metabolic rate of quiet sitting and standard MET values range from 0.9 (sleeping) to 18 (running at 17.5kph) with activities such as moderately heavy housework rated at 4.5 MET, low-impact aerobic

exercise at 5.0 MET and jogging at 7kph rated as 7.0 MET (Ainsworth et al., 2000). Corresponding MET values for the CHAMPS questionnaire are 3.0, 3.5 and 7.0 METs respectively.

The Lower Limb Task Questionnaire (McNair et al., in press) is a 20-question Likert scale that provides a measure of physical ability in subjects with lower limb dysfunction as related to performance of activities of daily living and recreational activities (see Appendix 9). Subjects were asked to rate their difficulty performing a task in the last 24 hours (4= 'no difficulty', 0 = 'unable') and the importance of each task in their daily life (rated 1= 'not important' to 4 = 'very important'). Where a task had not been performed in the last 24 hours, subjects were asked to record a best estimate. For this study, 'task difficulty', and not 'task importance', was scored for both the control and subject groups. Scores for both the ADL subset and the recreation subset range from 40 for 'normal with full functional capacity' to 0 for 'maximum incapacity'.

3.3 Procedures

All procedures were approved by the Northern X Regional Ethics Committee (approval number NTX/05/11/147, see Appendix 1). Testing was conducted in a small gymnasium in the local physiotherapy department, during normal working hours. All subjects were tested by the principal investigator, with testing conducted intermittently over a period of six months.

If the subject met all inclusion criteria a consent form was signed and testing began (see Appendix 10). Height and weight measures were recorded (EKS 9550AM Electronic Glass Scale, EKS International AB, Smaalandsstenar Sweden; Johnson Measures & Weights Ltd Wall-mounted Measuring Tape, Kowloon, Hong Kong) prior to commencement of testing.

3.3.1 Subject positioning

Subjects were positioned in a custom-built chair with their hip and knee joints at 90˚ of flexion. Pilot testing revealed that subject position and a consistent test technique were maintained by grasping arms on the test chair. A back support

(Bassett lumbar support, Bassett Lumber Support Co Pty Ltd, Londonderry N.S.W) was positioned to maintain a neutral lumbar lordosis during testing. Subjects were positioned so that their test knee was vertically aligned over the centre of the strain gauge.
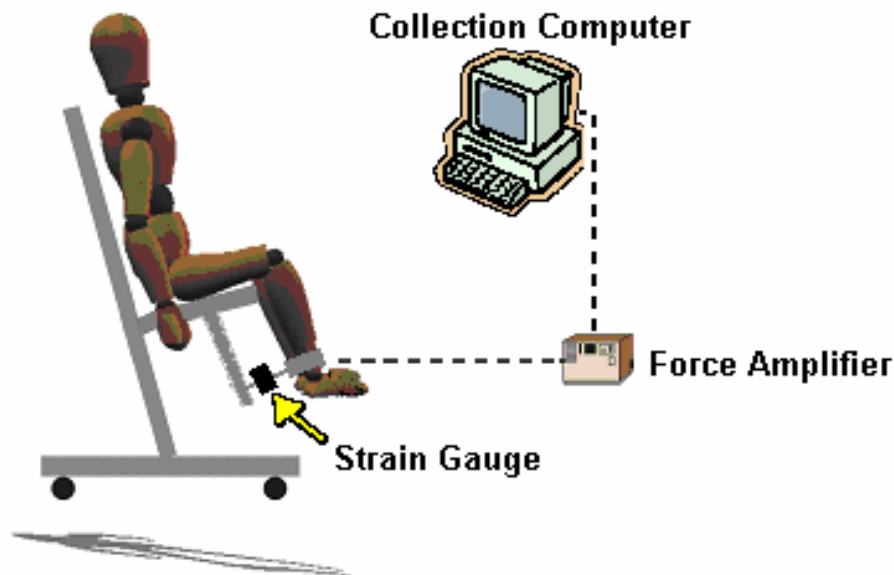

 Figure 3.1. Experimental set up

The chair was adjusted to ensure that the back of the knee rested comfortably against the edge of the seat. Just above the lateral malleolus, the lower leg was strapped to a very lightly padded metal attachment that was connected to a steel beam with a strain gauge connected in series. Comfort and skin integrity were maintained by using a felt-covered heat-moulded thermoplastic brace between the subject's skin and the Velcro straps that were used to secure the leg.

3.3.2 Force measurements

A PST model, 250kg maximum strain gauge (Precision Transducers Ltd, 7 Market Place, Glenfield, Auckland, New Zealand) was used to measure force. Signals were collected from the strain gauge and amplified by a custom-made amplifier and thereafter relayed to a personal computer sampling at 2000Hz. A real-time force trace was displayed on the computer monitor using a customised software package (Testpoint version 5, Capitol Equipment Corporation,

Massachusetts, USA). The Testpoint programme provided visual feedback of forces generated by subjects during maximal and submaximal tests. The calibration of the strain gauge was checked prior to each testing session.

3.3.3 Order of testing

Subjects were tested as follows:

1. Warm-up on stationary bike (or brisk walking)
2. Familiarisation with test equipment and MVC protocol for knee extensors
3. Maximal voluntary contraction (MVC) testing of knee extensors
4. Force estimation of submaximal isometric contractions at 10, 25, 50 and 75% of MVC of knee extensors
5. Serial isometric force matching tests at 10, 25 and 50% of MVC of knee extensors
6. Steps 3–5 repeated for the knee flexors
7. Force estimation of submaximal isometric grips at 10, 25 and 50% of maximum grip strength.

Presentation order of testing (for force estimation and force matching tasks) was derived from random number tables generated using the Research Randomizer programme (Urbaniak & Plous, 1997).

3.3.3a Warm-up
Prior to positioning in the test chair, subjects undertook a five-minute warm-up on a stationary cycle at a self-determined low-intensity level of exertion. Those subjects in the osteoarthritis group that were unable to comfortably use the stationary cycle completed five minutes of moderate intensity walking along a level corridor adjacent to the testing room.

Once seated in the test chair, a lever arm measure was recorded (in metres) from the lateral knee joint line to the point on the lower leg perpendicular to the centre of the strain gauge. Subjects performed an isometric warm-up protocol to help with familiarisation and to reduce the risk of injury prior to obtaining maximal voluntary contraction recordings. The protocol consisted of five submaximal isometric contractions held for five seconds, at 20-second intervals

and of increasing intensity. Subjects were then asked to perform contractions at half their perceived maximum, and then at three quarters of their maximum isometric capacity. Subjects were asked if they felt ready to commence testing. Further warm-up contractions were performed if requested by a subject.

Subjects were then rested for approximately three minutes during which time they were instructed in the use of MVC test procedures and pain and perceived effort scales. Subjects were taught to use an 11-point numerical pain scale (0 = no pain, 10 = excruciating pain) to allow pain levels to be monitored during testing (Farrar, Portenoy, Berlin, Kinman & Strom, 2000; Farrar, Young, LaMoreaux, Werth & Poole, 2001). To enable the recording of perceived effort, subjects were shown a modified Borg scale (Borg, 1982; Noble, 1982) and instructed to base their Borg ratings on muscle exertion during test contractions rather than a global rating of 'task' effort or mental effort.

3.3.3b Maximum voluntary contraction

Two practice attempts were undertaken with a two-minute interval between trials. The maximum voluntary contraction was defined as the highest force achieved by the subject over three trials, separated by two-minute rest periods (Morton et al., 2005; Newman, Jones, & Newham, 2003; Yoon, Park, Kang, Chun & Shin, 1991). Subjects were instructed to contract their muscle maximally, during which they received standardised verbal encouragement to facilitate a maximum effort (McNair, Depledge, Brettkelly & Stanley, 1996). The force generated was displayed on the screen of a PC monitor to provide visual feedback.

3.3.3c Force estimation in the lower limb

The lower limb force estimation protocol chosen for this study was heavily influenced by the methodologies reported in the studies by West and colleagues (2005) and Jackson and Dishman (2000). The methodology utilised by West et al. (2005) was modified to include a 10% MVC estimation level and incorporated testing of the antagonistic muscle group.

In random order, blindfolded subjects were asked to estimate and perform contractions at 10%, 25%, 50% and 75% of their MVC. Firstly, subjects were

instructed to perform a short-duration maximal contraction whilst concentrating on local muscle sensations (as opposed to skin pressure sensation from the fixation strap or chair). This maximum contraction was performed to orient the subject to the sensation of a 100% muscle contraction. Care was taken to ensure instructions regarding muscle sensation were open and devoid of terms that would influence perception (Jones, 1995). Subjects were then asked to perform the submaximal contraction basing their effort on perceived muscle sensation. Once force trace recordings were activated, subjects commenced their contraction responding with 'now' once they perceived they had reached their target and then holding this level for 2–3 seconds. On hearing the 'now' the examiner recorded the perceived match point via computer mouse-click using the Testpoint interface. Pilot testing revealed a time lag of less than 200 milliseconds between a subject saying 'now' and the examiner's mouse-click.

These contractions lasted approximately five seconds. The desired reference force, the subject's comparison force and the time taken to reach match-point were recorded for each of the four submaximal targets. Subjects performed one trial per submaximal target. Extra trials were performed if the subject failed to say 'now'; if results showed a clear misunderstanding of procedure; or if the subject indicated they wished to re-attempt the trial. Pain and effort scores were recorded at the end of each contraction. Subjects were not given any feedback regarding force matching performance.

3.3.3d Force matching in the lower limb

The force matching protocol used in this study was derived in part from the work on shoulder muscle force matching by Dover and Powers (2003). Their ipsilateral isometric force matching protocol was adapted for use in the flexor and extensor muscles of the knee. The incorporation of testing at multiple submaximal loading levels, with knee joints positioned in mid-range flexion, was based on findings from contralateral force matching protocols used by Jones, Hunter and colleagues (various) and Weerakkody, Percival and colleagues (various). Pilot testing revealed that the 75% MVC matching tests were uncomfortable and tiring for most individuals (pilot tests included younger and older adults) thereby constituting a risk to subjects with osteoarthritis so they were withdrawn from the force matching protocol.

The ipsilateral protocol used in the current study was adopted to minimise the potential confounding effect of differing maximum voluntary capacities between limbs. Secondly, the use of serial matching trials within a single muscle group limited the effect of fatigue and pain on force matching acuity as fatigue or pain influenced reference and comparison efforts equally. Lastly, the choice of ipsilateral tests considerably widened the pool of potential subjects by removing any requirement to exclude for dysfunction in the opposite limb.

In random order, subjects were asked to estimate and perform paired contractions at 10%, 25% and 50% of their MVC. A 75% MVC test was not included in this phase of the study after pilot testing at this level generated excessive fatigue and discomfort. Subjects performed sustained submaximal contractions (15–20 seconds), at the aforementioned levels, using visual feedback (via PC monitor) of force. Subjects were then blindfolded and asked to repeat the sustained contraction without feedback after a 20-second rest. Subjects indicated when they were at the target level and they held this level for 10–15 seconds.

Subjects performed three trials per submaximal target in a randomly presented order. Extra trials were performed if the subject failed to say 'now'; if results showed a clear misunderstanding of procedure; or if the subject indicated they wished to re-attempt the trial. Pain and effort scores were recorded at the end of the final paired contraction for each force level (10%, 25% and 50% MVC). Subjects were not given any feedback regarding force matching performance for any of the trials in this phase.

3.3.3e Force estimation utilising handgrip

Grip estimation tests were undertaken to determine whether force appreciation differences between groups, if apparent, were specific to muscles of the knee joint or were in fact evidence of more global force-coding discrepancies.

Force acuity was measured in the upper limb by way of a force estimation technique using a hand dynamometer (Sammons Preston, Bolingbrook, IL, USA). This test device allows a measure of grip strength in kilograms and displays the maximum level of force produced during a test grip. This force

reading is displayed until the unit is returned to zero again. After a familiarisation and warm-up period, subjects performed three maximal grips using their dominant hand. The maximum voluntary grip was defined as the highest force achieved over the three grips, performed at two-minute intervals. Three trials per submaximal grip level were randomly presented at levels of 10%, 25% and 50% of maximum grip. Subjects were instructed to gently squeeze the device until they felt they had achieved their target level and then relax. The force produced was then recorded. Pain and effort scores were not recorded in this phase of testing.

3.4 Data reduction

3.4.1 Force measurements

For lower limb tests, the results of maximal contraction, force estimation and force matching tasks were recorded in Newtons (N) and converted to torque (Nm).

3.4.2 Relative score

Estimation and matching errors were expressed relative to the desired submaximal target forces to allow meaningful comparisons between target levels, muscles and groups. This 'relative score' was derived by dividing the comparison force (torque produced) by the reference force (target torque) and is described further in Appendix 2.

Relative score (RS) = torque produced / target torque

The primary variable of interest in this experiment was normalised degree of error (RS) in estimating force generated at each of the target loadings for force estimation (knee extensors, knee flexors and grip) and force matching tasks (knee extensors, knee flexors).

3.4.3 'Time to decide'

The time taken to reach perceived match point during acuity tasks was recorded. The category 'time to decide' (TTD) describes the time lapse between the 'start' instruction given for each trial and the point at which the subject indicated they perceived that they had reached the target point by saying 'now' and is recorded in seconds. It should be noted that subjects were not instructed nor required to reach target force levels rapidly.

3.5 Statistical analysis

Statistical tests were undertaken using the Statistical Package for Social Services V11 (SPSS Inc, Chicago, IL, USA). For inferential tests the alpha level was set at 0.05.

Data was checked for outliers and normality to determine appropriate statistical tests. T-tests were used to identify and establish any differences between the two groups (osteoarthritis and control subjects) in age, body mass index, and questionnaire scores (excluding the PARQ), while peak torque values were compared utilising the Mann-Whitney-U test.

With respect to force estimation acuity a three-factor repeated analysis of variance (ANOVA) was used to assess difference across groups (OA, control), muscle group (knee extensors, knee flexors) and levels of muscle force (10%, 25%, 50%, 75% MVC). Sphericity assumptions were checked and, where necessary, Greenhouse-Geisser corrections were applied. Contrasts after ANOVA involved Bonferroni tests. These same analyses were repeated for the force matching acuity data with factors of group by muscle by level (10%, 25%, 50% MVC).

The variables of pain and perceived effort were individually correlated with mean RS scores for force matching and force estimation at the 50% MVC levels. Time to decide was correlated with RS scores for force matching and force estimation at the 25% MVC levels.

4. RESULTS

4.1 Introduction

This section is divided into five parts. The initial section describes demographic data regarding study participants and includes the pre-test pain and function questionnaires. The second section describes the maximum voluntary contraction results from both the lower limb muscle groups. The third section includes the comparisons for the force estimation tasks at the knee. The fourth section provides the comparisons for the force matching tasks at the knee. The fifth section contains results of the force estimation task using the hand grip dynamometer.

4.2 Participant characteristics

4.2.1 Control and osteoarthritis subjects

Forty-eight individuals fitted the inclusion criteria and were booked in for testing. Two controls were excluded from testing after final screening (one control had had cataract surgery within the last seven days; one control had forgotten their nitro-lingual spray). Two subjects directed back to their general practitioner on the basis of PARQ answers were advised to withdraw from the study. One subject was excluded at the final screening stage after reporting having just been fitted with telemetry for cardiac monitoring. A male subject was withdrawn from the study as a result of injury during his initial MVC attempt.

The results reported in this chapter refer to data that was collected from 21 subjects with osteoarthritis of the knee joint (see Table 4.1) and 23 control subjects (see Table 4.2). Two female subjects failed to complete all testing. Testing was terminated by the investigator because of increasing knee pain during isometric knee extension trials (one subject completed all the knee extensor tests, while the second subject completed knee extensor and knee flexor tests for the force estimation task only). Usable results from these two subjects have been included for data analysis.

Table 4.1. Osteoarthritis subject information

OA	Age (yrs)	Height (m)	Weight (kg)	BMI (kg/m²)
Male (n=9)	69.2 ± 5.2	172.1 ± 7.7	92.1 ± 19.4	31.0 ± 6.2
Female (n=12)	69.8 ± 6.8	159.1 ± 7.2	86.9 ± 18.7	34.3 ± 6.2
Overall (n=21)	69.6 ± 6.0	164.7 ± 9.8	89.1 ± 19.4	32.9 ± 6.5

Values are group means ± SD. BMI = body mass index.

There were significant differences ($p < 0.05$) in age and BMI between control and osteoarthritis groups; however, *post hoc* correlations showed no significant relationship ($p > 0.05$) between age nor BMI and force acuity scores.

Table 4.2. Control subject information

Control	Age (yrs)	Height (m)	Weight (kg)	BMI (kg/m²)
Male (n=11)	62.5 ± 7.6	170.1 ± 5.0	73.6 ± 10.8	25.5 ± 3.7
Female (n=12)	60.8 ± 8.0	158.8 ± 8.1	71.0 ± 11.9	28.3 ± 5.0
Overall (n=23)	61.6 ± 7.6	164.3 ± 8.8	72.3 ± 11.2	27.0 ± 4.6

Values are group means ± SD. BMI = body mass index.

The right knee was tested in all but one of the control group; a male subject who had had a recent skin tear on his right shin. The right knee was tested in 12 of the 23 osteoarthritis subjects. There were no significant differences ($p > 0.05$) between left and right lower limb results within groups, therefore, for the purpose of analysis, all results were grouped together.

4.2.2 Pain and function questionnaire scores

Table 4.3. WOMAC scores

Group	Pain (0-20)	Stiffness (0-8)	Function (0-68)	Total (0-96)
Control	0.2 ± 0.6	0.4 ± 0.8	0.7 ± 1.4	1.4 ± 2.8
OA	7.5 ± 3.5	3.8 ± 1.7	29.2 ± 10.7	40.5 ± 15.9

Values are group means ± SD. WOMAC = Western Ontario and McMaster Universities Osteoarthritis Index.

The WOMAC and Lower Limb Task Questionnaire (LLTQ) scores were clearly different between groups for all pain and function subscales ($p<0.05$) (see Tables 4.3 and 4.4).

Table 4.4. Lower Limb Task Questionnaire scores

Group	LLTQ-ADL (40-0)	LLTQ -Recreation (40-0)
Control	39.4 ± 1.5	35.8 ± 5.1
OA	20.7 ± 6.1	9.7 ± 12.1

Values are group means ± SD. Numbers in brackets indicate the range of possible scores (from least to most pain or dysfunction). ADL = activities of daily living.

Osteoarthritis subjects were markedly less active than their healthy peers. CHAMPS scores revealed significant differences ($p<0.05$) in both weekly accumulation and duration of exercise between the groups (see Table 4.5).

Table 4.5. CHAMPS Physical Activity Questionnaire

Group	Exercise accumulation (MET*/week)	Exercise duration (hrs/week)
Control	5298.4 ± 3460.7	21.2 ± 13.5
OA	3364.2 ± 2530.5	12.3 ± 8.7

Values are group means ± SD. *MET = metabolic equivalents where
1 MET ≈ 1 kcal·kg^{-1}·hr^{-1}

4.3 Maximum voluntary torque production

4.3.1 Maximum strength

Figure 4.1 shows peak torque in the knee flexor and knee extensor muscles for the control and osteoarthritis groups. Peak knee flexor torque levels were similar in the control and OA groups ($p > 0.05$) with values of 45.4 Nm (SD±18.7) in the control group and 46.1 Nm (SD±15.4) in the osteoarthritis group.
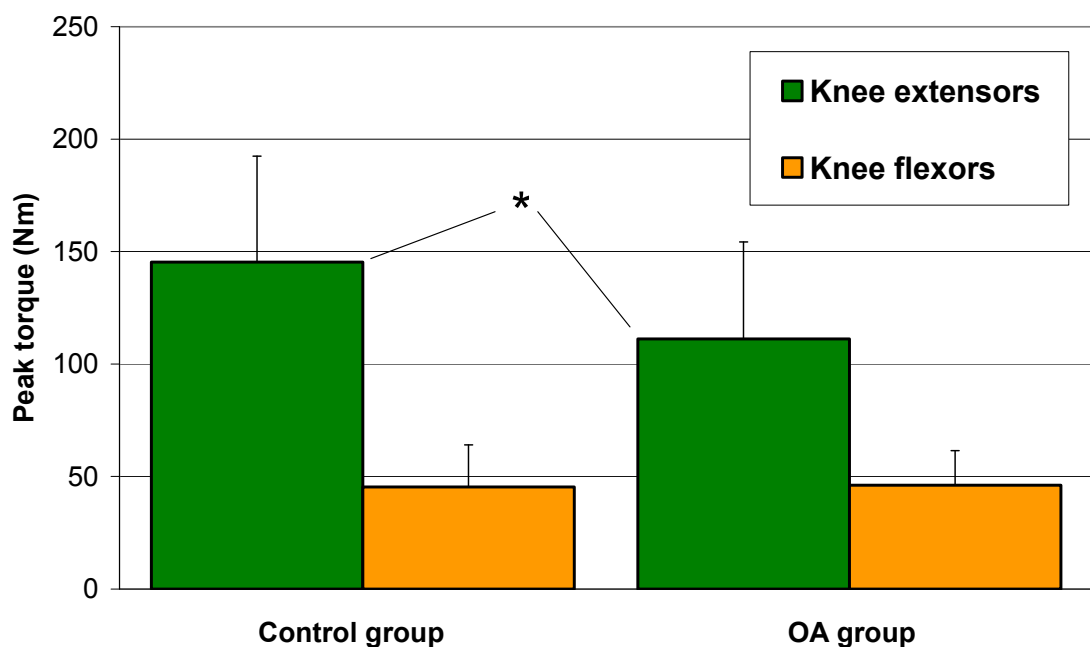
Figure 4.1. Mean peak torque data

* Indicates a significant difference ($p > 0.05$) between subject groups. Data are means and SD.

There was a significant difference (p<0.05) in peak knee extensor torque between control and osteoarthritis groups. Peak knee extensor torque was 145.3 Nm (SD±47.2) in the control group and 112.9 Nm (SD±43.3) in the osteoarthritis group.

4.3.2 Pain and perceived exertion during maximum torque production

Osteoarthritis subjects experienced pain (1–2/10) during peak torque testing. Values of this magnitude do not represent a clinically important pain intensity difference (Farrar et al., 2000). There was no difference between groups in perception of effort ratings during maximal contractions. All participants scored MVC trials at 10 on the modified Borg scale.

4.4 Force estimation task in the lower limb

This section presents the results of force estimation comparisons and includes pain scores, ratings of perceived exertion and time-to-decide measures for the lower limb force estimation tasks.

4.4.1 Force estimation acuity
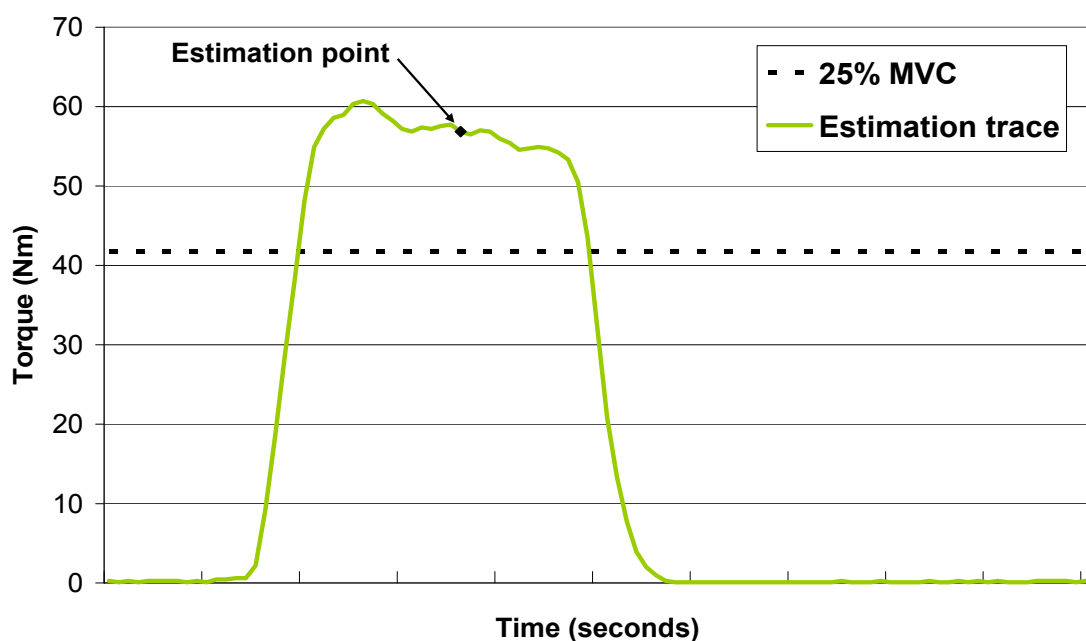
Figure 4.2. Force trace for 25% MVC knee extensor estimation task

The point at which the subject indicated he was at 25% MVC is shown by the diamond symbol and arrow.

Figure 4.2 shows a 10-second force trace obtained from a single male control subject during a 25% MVC force estimation test of the knee extensor muscles. Table 4.6 presents relative scores for force estimation tasks for each group and each muscle tested.

Table 4.6. Relative scores for force estimation tasks

	Control knee extensors	OA knee extensors	Control knee flexors	OA knee flexors
10% MVC	1.91 ± 1.19 (0.52–4.53)	2.24 ± 1.57 (0.27–8.08)	3.11 ± 1.21 (1.02–5.66)	2.34 ± 1.31 (0.52–5.67)
25% MVC	1.11 ± 0.44 (0.48–2.05)	1.36 ± 0.51 (0.56–2.48)	1.75 ± 0.55 (0.66–2.75)	1.48 ± 0.61 (0.51–2.75)
50% MVC	0.84 ± 0.24 (0.29–1.35)	0.91 ± 0.28 (0.43–1.45)	1.16 ± 0.26 (0.78–1.68)	1.02 ± 0.30 (0.47–1.58)
75% MVC	0.74 ± 0.18 (0.28–1.02)	0.79 ± 0.20 (0.44–1.37)	0.87 ± 0.17 (0.59–1.24)	0.81 ± 0.17 (0.55–1.07)

Values are group means ± SD, range in brackets.

A main effect for muscle group ($p<0.05$) and submaximal force level ($p<0.05$) was noted (see Figure 4.3). However, a significant ($p<0.05$) three-way interaction effect was apparent between variables (see figures 4.3 and 4.4). While figures 4.3 and 4.4 show similar data, the line graph (4.4) provides a clearer appreciation of interaction across the variables.

Across submaximal levels, a pattern of overshooting lower target force levels and undershooting higher target force levels was observed. A significant ($p<0.05$) muscle by force level interaction showed that the pattern of changing estimation acuity across submaximal force levels was different for each muscle group. For knee extensors, the lower two levels were overestimated and the higher two target levels underestimated. In contrast, for knee flexors, targets were only underestimated at the 75% MVC level (see Figure 4.3). Furthermore, the difference between 10% and 25% MVC in flexors of the control group was notably different from the other conditions.
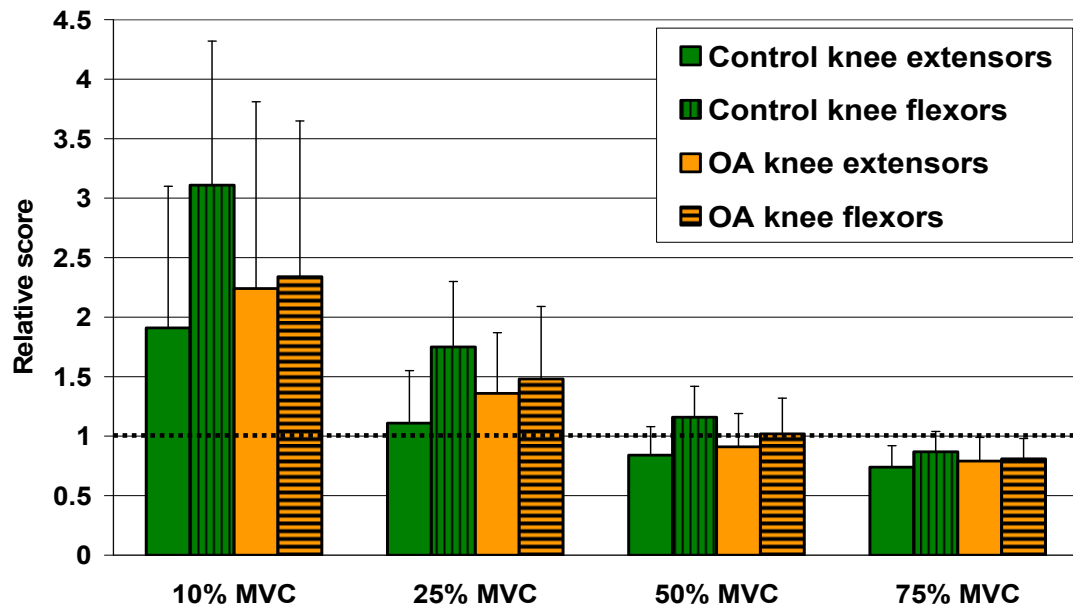
Figure 4.3. Relative scores for force estimation at the knee – bar graph.

Data are means and SD.   The dashed line represents perfect force estimation.

The significant ($p<0.05$) muscle-by-subject-group interaction indicated that force estimation for knee extensors and knee flexors was different across subject groups. In this respect, across extensors relative scores were lower in the control group, whereas across flexors relative scores were lower in the osteoarthritis group.
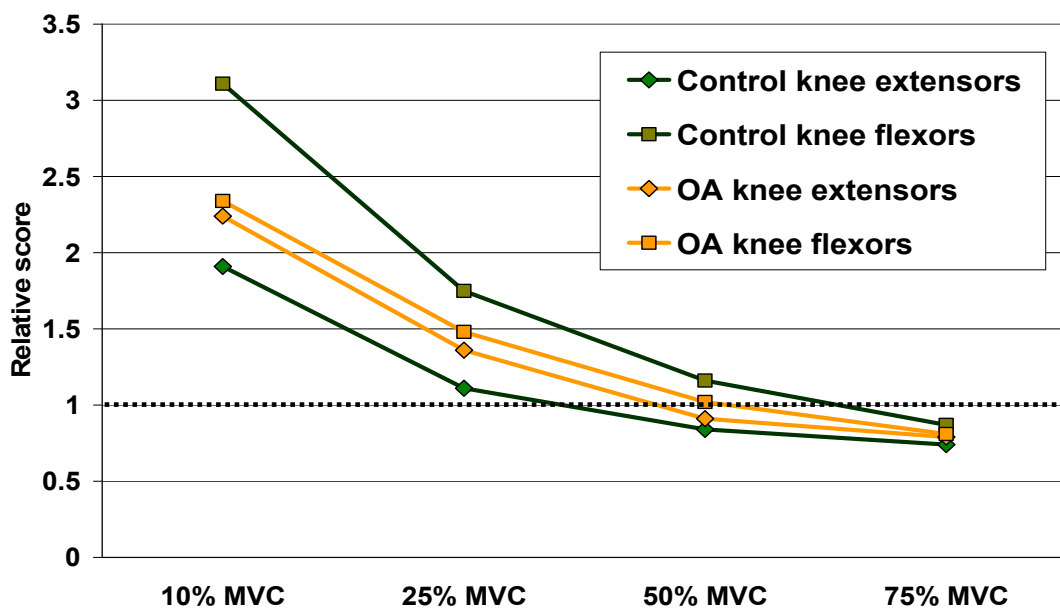

Figure 4.4. Relative scores for force estimation at the knee – line graph

Data is mean relative scores. The dashed line represents perfect force estimation.

Although the submaximal force level by subject group interaction was not significant ($p > 0.05$), it should be noted that the variation in force estimation acuity between the 10% and 25% MVC level across subject groups showed a strong trend to significance ($p = 0.05$).

4.4.2 Pain and rating of perceived exertion scores during force estimation

Control subjects reported no pain at all levels during force estimation tests. Osteoarthritis subjects reported minimal pain during force estimation tests, with the osteoarthritis group mean reaching a peak, at 75% MVC, of 1.2 for knee extensors and 1.2 for knee flexors. As mean peak pain levels for all groups at all levels were under 2, pain levels were regarded as minimal and not clinically significant (Farrar et al., 2001).

Ratings of perceived exertion increased significantly ($p < 0.05$) between submaximal force levels but no significant differences ($p > 0.05$) were noted between subject groups or muscles (see Figure 4.5).
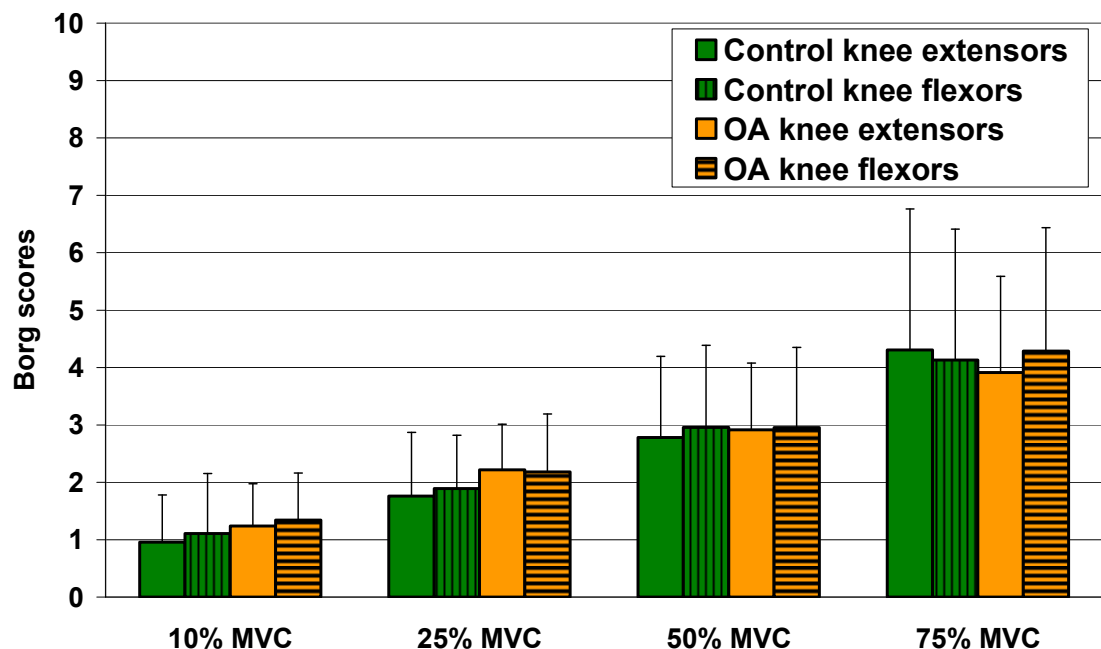
Figure 4.5. Rating of perceived exertion scores across subject and muscle groups in the force estimation task

Data are means and SD.

4.4.3 Time-to-decide and force estimation acuity

A comparison of time-to-decide values across control and OA subjects was undertaken at the 25% MVC level for both knee extensors and knee flexors. This level was chosen arbitrarily but is representative of a force level that is thought to be used often during normal activities of daily living. There was no significant difference ($p>0.05$) for time to decide at this force level across both subject groups and muscle tested.

4.5 Force matching task in the lower limb

This section presents the results of force matching comparisons and includes pain scores, ratings of perceived exertion and time-to-decide measures for the lower limb force matching tasks.

4.5.1 Force matching acuity
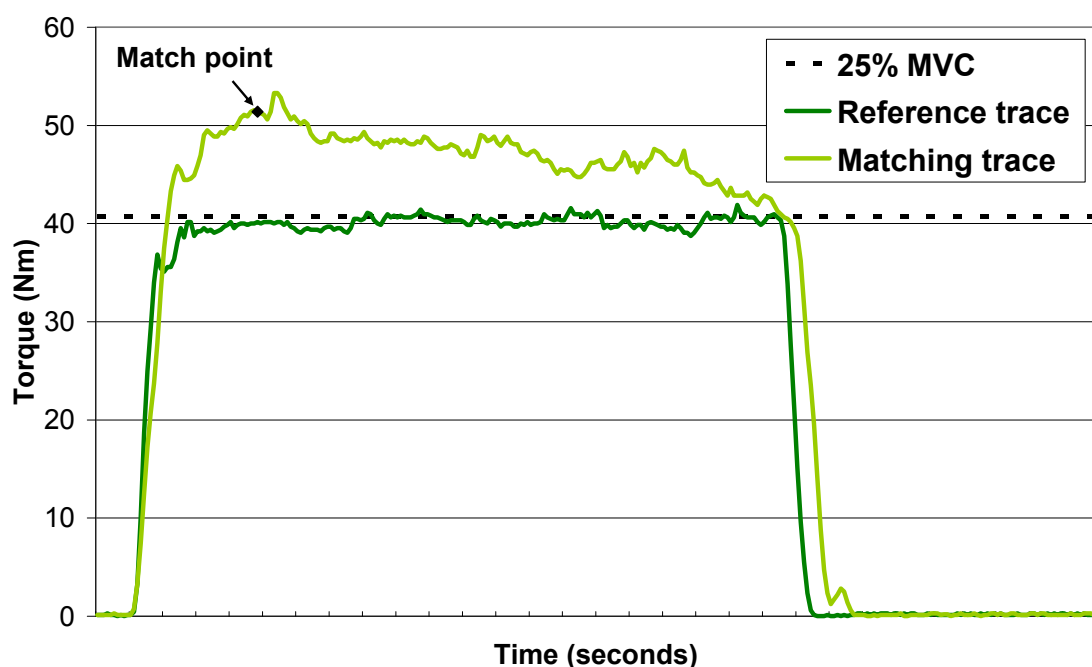
Figure 4.6. Force traces for 25% MVC knee extensor matching task

The point at which the subject indicated she was at 25% MVC is shown by the diamond symbol and arrow.

An example of force matching traces obtained from a single female control subject at the 25% MVC level for the knee extensor is displayed in Figure 4.6. Both reference and matching traces are included in this figure with traces recorded over a 30-second epoch. Table 4.7 presents relative scores for force matching tasks for each group and each muscle tested.

Table 4.7. Relative scores for force matching tasks

	Control knee extensors	OA knee extensors	Control knee flexors	OA knee flexors
10% MVC	1.43 ± 0.54 (0.56–2.68)	1.42 ± 0.36 (0.58–2.11)	1.70 ± 0.61 (0.55–3.18)	1.93 ± 0.61 (0.80–3.06)
25% MVC	1.20 ± 0.25 (0.75–1.72)	1.12 ± 0.20 (0.67–1.46)	1.47 ± 0.44 (0.97–2.96)	1.35 ± 0.33 (0.60–1.89)
50% MVC	1.10 ± 0.13 (0.86–1.33)	1.07 ± 0.15 (0.80–1.32)	1.21 ± 0.20 (0.86–1.72)	1.17 ± 0.16 (0.89–1.46)

Values are group means ± SD, range in brackets.

Main effects for muscle group ($p < 0.05$) and submaximal force level ($p < 0.05$) were found (see Figure 4.7). Whilst the three-way interaction between these variables was not significant ($p > 0.05$), a trend towards an interaction effect ($p = 0.066$) was noted (see Figure 4.8).

Knee flexors had higher relative scores than those produced with the knee extensors (see Figure 4.7). A pattern of overshooting target force levels was observed for all subjects. The extent of overshooting decreased as submaximal force levels increased. There was a significant ($p < 0.05$) interaction effect for muscle group such that the reduction in matching errors across submaximal forces levels was more pronounced in the knee flexor muscles (see Figure 4.7).
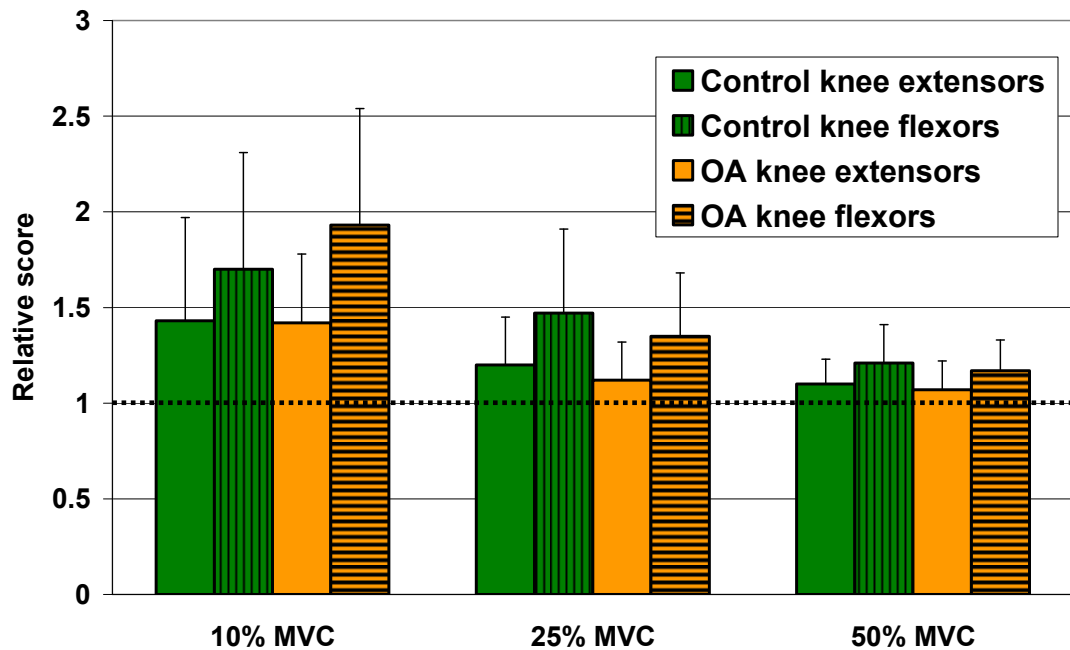
Figure 4.7. Relative scores for knee force matching – bar graph

Data are means and SD. The dashed line represents perfect force matching.

A muscle-by-subject group interaction was not significant ($p > 0.05$), indicating that force matching acuity between muscle groups was similar for control and osteoarthritis groups (see Figure 4.8).
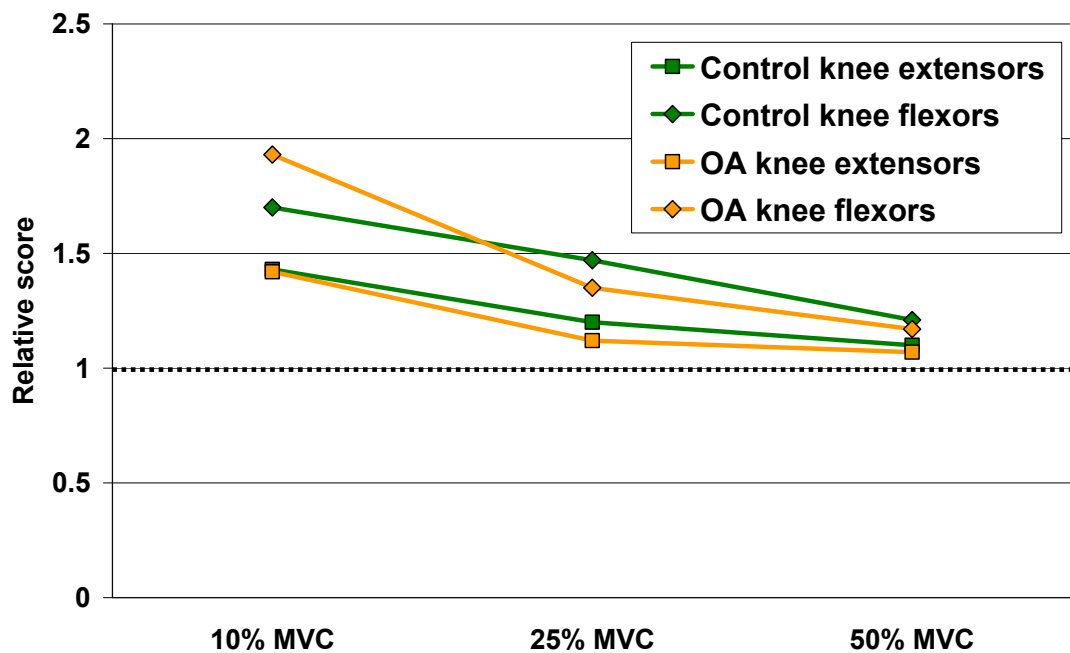

Figure 4.8. Relative scores for knee force matching – line graph

Data are means and SD. The dashed line represents perfect force matching.

A submaximal force level by subject group interaction was not significant (p>0.05) but trend was observed (p=0.080).

4.5.2 Pain and rating of perceived exertion scores during force matching

Some subjects in the control group reported pain during the force matching tasks, but at all levels and for both muscles group means scores were well under clinically significant levels (0.7 and 0.7 for 50% MVC tasks in knee extensors and knee flexors respectively). The osteoarthritis group reported mild pain during matching tasks. Only knee extension at the 50% MVC level caused clinically significant pain ($\bar{x}$ = 3.0) for the osteoarthritis group (Farrar et al., 2000). Therefore a *post hoc* analysis was undertaken at the 50% MVC level examining whether pain at this level was related to force matching acuity. The analysis showed that no such relationship existed (knee extensors, *r* = 0.372. p>0.05; knee flexors, *r* = -0.157, p>0.05).

As with the force estimation tasks, ratings of perceived exertion increased significantly (p<0.05) across levels but no significant differences (p>0.05) were noted between subject groups or muscles (see Figure 4.9).
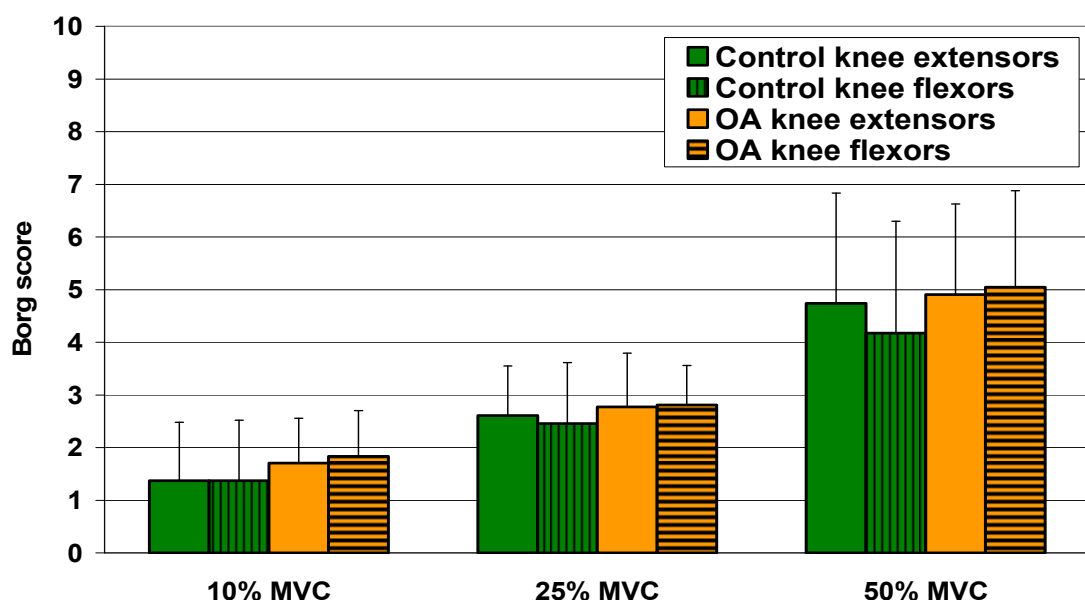
Figure 4.9. Rating of perceived exertion scores across subject and muscle groups in the force matching task

Data are means and SD.

4.5.3 Time-to-decide and force matching acuity

A comparison of time-to-decide values across control and osteoarthritis subjects was undertaken at the 25% MVC level for both muscle groups. There was no significant difference ($p > 0.05$) in time-to-decide values during force matching.

4.6 Grip force estimation

There was no significant difference ($p > 0.05$) in peak grip strength between the two subject groups (see Table 4.8).

Table 4.8. Maximum grip strength

Group	Hand grip (kg)
Control	28.74 ± 9.69
OA	29.33 ± 9.34

Values are group means ± SD.

Table 4.9. Relative scores for grip estimation

	Control grip	OA grip
10% MVC	1.50 ± 0.83	1.96 ± 1.34
	(0.20–4.05)	(0.39–5.56)
25% MVC	1.17 ± 0.50	1.34 ± 0.56
	(0.48–2.44)	(0.47–2.78)
50% MVC	1.04 ± 0.20	1.00 ± 0.25
	(0.68–1.70)	(0.50–1.72)

Values are group means ± SD, range in brackets.

The pattern of overestimating lower submaximal target levels demonstrated during lower limb tasks persisted for force at the hand (see Table 4.9 and Figure 4.10).
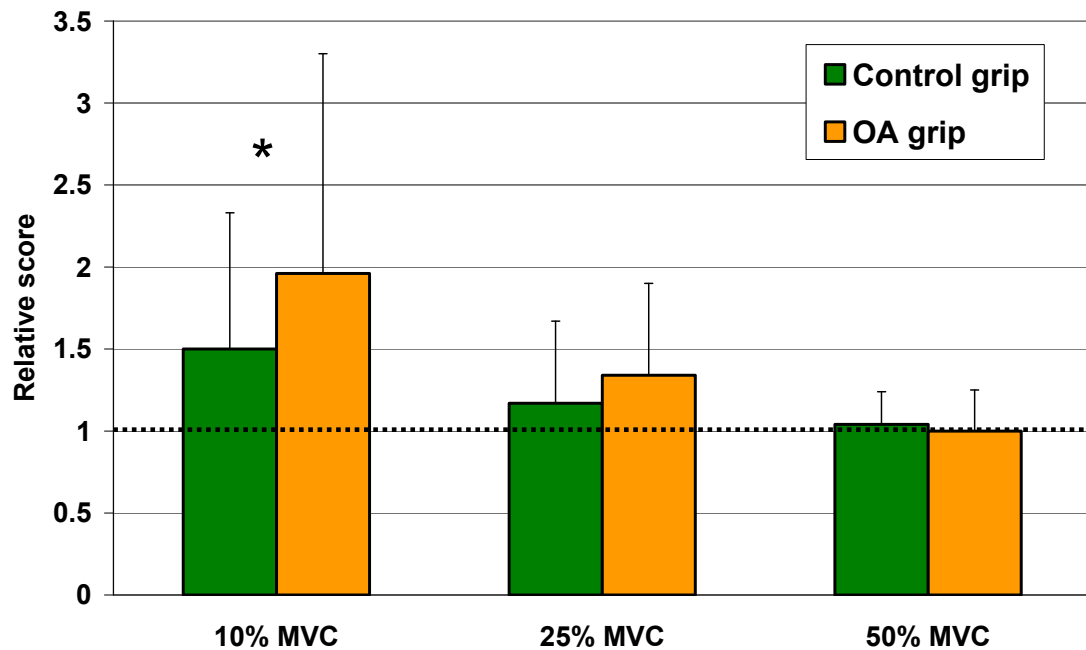
Figure 4.10. Relative scores for grip force estimation

* Indicates a significant difference between subject groups (p<0.05). Data are means and SD. The dashed line represents perfect force matching.

There was a significant main effect (p<0.05) for level during force estimation. However, a force-level-by-group interaction was significant (p<0.05). At the 10% MVC control subjects demonstrated significantly better force estimation ability than osteoarthritis subjects (see Figure 4.10).

5. DISCUSSION

This chapter is divided into three sections. The first section discusses the results pertaining to subject characteristics, questionnaire scores and maximal voluntary capacity results. The second section comprises a discussion of the results of force appreciation tests, including comparisons with previous studies, and a brief discussion of the mechanisms that may have contributed to the findings. The final section briefly explores the significance of findings to the assessment and management of osteoarthritis, including suggestions for further research and recommendations for physiotherapy practice.

5.1 Subject data, questionnaires and strength tests

5.1.1 Subjects

A major strength of this study was the relatively large number of participants who completed testing. Of the 51 studies reviewed, 30 reported total participant numbers at lower than 20 (control and subjects combined). Excluding studies related to oral function, handedness, and those involving young children, only 11 studies had total participant numbers over 20 and of these only six studies reported similar or larger subject numbers than that of the current study. In all but two of these six studies, subject groups were composed entirely of healthy young adults. Only the Hortobágyi et al. (2004) study reported comparable subject numbers (n=20 each of OA and control subjects).

Subjects in the current study exhibited characteristics typically demonstrated by individuals with osteoarthritis including higher levels of reported pain at rest and during activities of daily living, a pattern of decreased lifestyle activity, higher body mass indices, and knee extensor strength deficits (Bennell et al., 2003; Felson, 2005; Slemenda et al., 1997; Steultjens et al., 2001; Vad et al., 2004).

5.1.2 Pain and function questionnaires

The mean WOMAC score from the subjects with knee joint osteoarthritis in the current study was 43.0 (SD±15.5) from a possible score of 96. This represents

a mean score of 41% of the maximum available and is typical of a group with moderate to severe osteoarthritis of the knee joint. The severity of pain and functional disability for osteoarthritis subjects in the current study compares well with work by Barker et al. (2004) and McHugh et al. (2007). Barker et al. reported WOMAC scores ranging from 45.6%–64.7% of the maximum score in 123 subjects in a study examining the association between radiographic classification of severe knee osteoarthritis and measurements of function, pain and power in older adults awaiting elective knee arthroplasty. McHugh et al. reported WOMAC scores ranging between 14.5% and 92.7% (mean 56.5%) of the maximum in 105 adults awaiting hip or knee joint replacement in a study investigating pain control, treatment and service provision amongst individuals with severe lower limb osteoarthritis.

The Lower Limb Task Questionnaire is a relatively new scale and, as such, comparison data from previously published studies is unavailable. In the current study marked differences were apparent between groups. Osteoarthritis subjects reported significantly more ($p < 0.05$) difficulty performing activities of daily living as well as undertaking recreational activities.

Metabolic equivalent values derived from the CHAMPS questionnaire indicate that the subjects with osteoarthritis of the knee tested in this study performed roughly 40% less exercise than their healthy counterparts in the month preceding testing. Values for both subjects groups fall within those previously published (Cyarto et al., 2006; Stewart et al., 2001a; Stewart et al., 2001b). To date there are no published data regarding CHAMPS scores specific to an osteoarthritis population group. Of interest, control subjects accumulated on average 1900 more metabolic equivalents a week than osteoarthritis subjects. This difference equates to 5.6 hours of heavy gardening (digging, mowing lawn) or 10.0 hours of light gardening (watering plants, tending pot plants) a week.

From these questionnaires it can be established that - at the time of testing - subjects with osteoarthritis of the knee joint reported they had substantial pain and joint dysfunction, they had difficulty performing activities of daily living and undertaking recreational activities and they were demonstrating reduced overall levels of activity and exercise participation compared to their healthy peers.

5.1.3 Maximum voluntary contraction

There was considerable variation in maximum voluntary contraction levels reported in literature concerning knee extension and knee flexion in subjects with and without osteoarthritis. Compounding attempts to compare MVC values from the current study with published data was the abundance of descriptors and unit measures used to describe and assess maximum strength. Additionally there appeared to be limited published data which described peak torque values for both knee extensors and knee flexors from the same subjects. As a result, the number of studies with similar subject characteristics that utilised an isometric peak torque methodology at 90° knee joint flexion was limited and made comparison difficult.

Mean peak voluntary torques of 112.9 Nm (SD ±43.3, range 42.7–198.2 Nm) for knee extensors and 46.1 Nm (SD ±15.4, range 22.3–77.9 Nm) for knee flexors in legs affected by osteoarthritis were recorded in the current study. Reported mean peak torque values in studies of older adults with osteoarthritis were comparable and ranged between 40 Nm and 130 Nm for knee extensors (Fisher et al., 1994; Fisher & Pendergast, 1994; Fransen et al., 2003; Goldman et al., 2003; Lin et al., 2001; Madsen & Brot, 1996; Schiffman et al., 2002; Steultjens et al., 2001) and 18 Nm to 98 Nm for knee flexors (Fisher et al., 1994; Fisher & Pendergast, 1994; Fransen et al., 2003; Goldman et al., 2003; Lewek et al., 2004; Madsen & Brot, 1996; Steultjens et al., 2001).

Control subjects produced mean peak voluntary torque of 145.3 Nm (SD ±47.20, range 62.3–235.0 Nm) for knee extensors and 45.4 Nm (SD ±18.7, range 14.3–110.2 Nm) for knee flexors. These values were within reported mean peak torque values for healthy older adults, which ranged from 70 Nm to 183 Nm for knee extensors (Madsen & Brot, 1996; Ordway et al., 2006; Pincivero et al., 2003) and 39 Nm to 83 Nm for knee flexors (Ordway et al., 2006; Silva et al., 2003).

The knee extensors of subjects with osteoarthritis were significantly weaker (p<0.01) than those of control subjects, a finding well-established in published literature (Kannus & Järvinen, 1990; Rossi, et al., 2006; Steultjens et al., 2001;

Yoon et al., 1991). In contrast, there was no difference between peak knee flexor torques between groups. This finding was at odds with the conclusions of Steultjens et al. (2001) and Yoon et al. (1991), who demonstrated significant differences in peak torque for both muscle groups between healthy and osteoarthritis subject groups. It was, however, similar to the findings of Slemenda et al. (1997) who demonstrated significantly lower peak knee extensor torque but not peak knee flexor torque in osteoarthritis subjects compared to age-matched control subjects, although it should be noted that peak muscle torque in the Slemenda study was assessed utilising isokinetic dynamometry at 60 and 120 degrees per second. This pattern of knee extensor deficit with normal knee flexor strength is supported in part by Ikeda et al., (2005) who demonstrated a quadriceps 'dominated' atrophy pattern in older women which was significantly correlated with levels of incident radiographic osteoarthritis.

5.2 Force appreciation acuity

The key finding of this study is that force estimation acuity is different in subjects with osteoarthritis. Subjects with osteoarthritis are less adept at estimating lower levels of submaximal force with their knee extensors and more adept at estimating lower levels of submaximal force with knee flexors than their healthy peers.

This is the first study to investigate the force estimation acuity of older adults (with and without osteoarthritis) in both knee extensors and knee flexors. Of the studies reviewed, only West et al. (2005) reported the use of a force estimation strategy involving extensor muscles acting on the knee joint. The results of young subjects (West et al., 2005) are comparable to those produced by the knee extensors in the current study.

The relative scores produced in the current study also compare favourably with those arising from bench press estimations as reported in the Jackson and Dishman (2000) study. Relative scores for force estimation acuity diminished as submaximal force levels increased and subjects were most accurate at the 50% MVC level in all three studies. There was however a difference in force

estimation acuity at low levels during isometric knee flexion when compared to the other studies. At the 25% MVC level, relative scores in the current study were higher for all but the control group knee extension task. Unfortunately, there is no published force estimation data available for comparison at the 10% MVC level.

Within the force estimation paradigm an arbitrary single test per submaximal force level was undertaken to improve manageability of the overall testing process. The use of single trials reduced the probability that results accurately indicated a subject's ability to estimate force. However, single test methodologies have been successfully used in force estimation testing (Jackson & Dishman, 2000; West et al., 2005). To reduce the impact of this sampling bias subjects were able to repeat their test at each level if they forgot to indicate their match point, if they felt they had performed badly or if the principal investigator felt they had misunderstood instructions.
A factor influencing poor acuity at the lowest force level may include the cognitive difficulty of estimating one-tenth of maximal voluntary capacity. The perceptual construct of 'half' and 'quarter' are easier to visualise than 'one-tenth'. Relative scores for 10% MVC were lower in the force matching tasks giving some support for this notion, given that during force matching the reference effort 'cued' subjects for the 10% level.

Force estimation acuity in knee extensors of the osteoarthritis group was less acute at lower submaximal force levels suggesting that the ability to accurately produce target forces is impaired in this population. The difference in peak torque may have influenced the disparity between group relative scores across the two muscle groups. Although submaximal levels were calculated from an individual's peak torque, the absolute interval between submaximal levels was greater for control subjects because of their higher peak knee extension torque. Having a greater 'range' of force-generating ability may have influenced force acuity; however, a lack of correlation (for subject group) between time-to-decide and force acuity at the 25% MVC level suggested this was not the case.

Whilst Hortobágyi et al. (2001) found that there was no correlation between maximal strength and force accuracy, they did find that low and high intensity

strength training effected significant improvements in force error and steadiness. There was no training component in the current study; however, the significantly higher level of lifestyle activity undertaken by the control subjects as evidenced by the CHAMPS and LLTQ scores may have had a de facto training effect for this group, potentially accounting for the differences seen in the force estimation task.

Regardless of subject group, significant differences ($p<0.05$) in force estimation acuity were noted between the two muscles tested. It is worth noting that in the current study, both subject groups reported that knee flexion estimation tasks were perceptually more difficult; an artefact that possibly points to the existence of a more 'developed' force sense in the knee extensor muscle group. The knee extensor and knee flexor muscles differ considerably in size, morphology, and function. The knee extensor muscles are predominantly uniarticulate, are composed of similar numbers of slow and fast twitch muscle fibre types, produce uniplanar joint motion and insert via a combined tendon to a single point below the knee joint (Wickiewicz, Roy, Powell & Edgerton, 1983; Williams et al., 1989a). The knee flexor muscles are predominantly biarticulate, have proportionally more fast than slow twitch muscle fibres, can produce biplanar movements, and insert into multiple sites around the knee joint (Wickiewicz et al., 1983; Williams et al., 1989a).

In light of these distinctions, it is possible that there are differences in the number and arrangement of intramuscular sensory receptors between these two muscle groups. The knee extensor muscle group is substantially larger than that of the knee flexor muscle group. Knee extensor volume is approximately three times that of knee flexor volume in healthy young adults (Trappe et al., 2001). This ratio is reduced due to quadriceps 'dominated' atrophy in healthy older adults, with ratios of 2:1 for knee extensors and knee flexors cross-sectional areas respectively (Engstrom, Loeb, Reid, Forrest, & Avruch, 1991; Ikeda et al., 2005; Tate, Williams, Barrance, & Buchanan, 2006). This ratio is reduced in the presence of joint pathology with a cross-sectional area ratio of almost 3:2 demonstrated for older women with osteoarthritis in the knee joint (Ikeda et al., 2005). The larger number of muscle fibres in the knee extensor muscle group, indicated by a higher cross-sectional area, (Wickiewicz et al.,

1983) suggests that the volume of intramuscular mechanoreceptors must be higher in this muscle group given that the ratios of Golgi tendon organs and muscle spindles to motor units is fairly similar across large mammalian muscles (Jami, 1990).

The level of force produced during a voluntary muscle contraction is controlled by the extent, rate and pattern of motor unit recruitment (Elder, Bradbury, & Roberts, 1982). Differences in force estimation acuity between muscle groups may reflect the difference in muscle fibre types as the knee extensor group is primarily heterogeneous with a mixture of slow and fast twitch motor units whilst the knee flexor muscles are primarily homogeneous with comparatively higher proportions of fast twitch motor units (Lexell, Taylor & Sjostrom, 1988; Wickiewicz et al., 1983; Williams, et al., 1989a).The efferent copy of motor output generated in the supplementary motor area (Haggard & Whitford, 2004) changes as, in accordance with Henneman's size principle, force generation demands cause a transition from predominantly low-threshold (slow twitch) motor unit activation to the recruitment of progressively more high-threshold (fast twitch) motor units (Henneman, Somjen & Carpenter, 1965). Homogeneity in motor unit type potentially limits the quality of data available for cortical coding and could account for the diminished force estimation acuity in the knee flexor muscle group seen in the current study. It is unlikely that this difference in slow to fast twitch motor unit ratios between muscles had an influence on peripheral mechanoreceptor output given that Gregory and Proske (1979) demonstrated that Golgi tendon organ responsiveness was not affected by the type of motor unit being activated.

Following on from this discussion on motor unit type, the force estimation deficit evident during knee extension tests by subjects with osteoarthritis may have arisen in part by morphological changes that occur with muscle atrophy. Trauma and disuse causes both slow and fast twitch muscle fibres (and therefore motor units) to atrophy considerably (Booth, 1982). However a number of studies have demonstrated that slow twitch fibres are significantly more affected (Goldspink, Morton, Loughna & Goldspink, 1986; Lieber, Fridén, Hargens, Danzig & Gershuni, 1988) producing a shift in the ratio of muscle fibre type towards a greater proportion of fast twitch fibres (Talmadge, Roy &

Edgerton, 1996). This shift may, as suggested above, affect the quality of force coding 'data'.

The length–tension relationship, which describes a muscle's maximal force-generating capacity as a function of sarcomere length, may have contributed to this finding (Gordon et al., 1966). Optimum force estimation accuracy has been shown to occur at muscle mid-length, with deteriorating accuracy at the inner and outer extremes of joint range (Cafarelli & Bigland-Ritchie, 1979; Weerakkody et al., 2003b). Testing in the current study was conducted with the knee joint positioned in 90° of flexion as this position is commonly adopted for maximal voluntary capacity testing at the knee joint. The 90° knee flexion test position would have meant knee extensors and knee flexors were tested at different points along the length–tension continuum. In this position, knee extensor muscles were slightly lengthened and knee flexors were slightly shortened. Although values were not specified in the Weerakkody study (2003b), graphic representation of results suggested that matching errors were substantially larger when the reference muscle was in a shortened position when compared with longer muscle positions. The direction of the differences noted in the current study reflect those of Weerakkody et al. (2003b), with the 'shortened' knee flexor muscles producing considerably larger estimation errors than the knee extensor muscles at the lower two submaximal levels.

It is possible that differences in peak torque between knee extensor and knee flexor muscles may have influenced force estimation ability, as the intervals between submaximal levels were greater for the knee extensor muscles. However, the lack of correlation (for muscle group) between time-to-decide and force acuity at the 25% MVC level suggests this was unlikely.

Joint restriction is a common feature of knee joint osteoarthritis (Szabo et al., 2000). When joint movement is restricted or lost, muscle length is adapted to the available range so that a functional length–tension relationship is maintained (Hortobágyi et al., 2000; Swynghedauw, 1986). If joint restriction was evident it is possible that the arbitrary 90° knee flexion position chosen for testing represented functionally different muscle lengths for the control and osteoarthritis subjects. Whilst it is possible that differences in relative muscle

length may have accounted for the reduced force estimation ability at lower submaximal test levels, this premise can not be substantiated as knee joint range of movement was not measured in the current study.

Grip force estimation acuity of osteoarthritis subjects was significantly worse (p<0.05) at the 10% MVC level and trended to significance (p=0.055) at the 25% MVC level compared to the control subjects. That force estimation ability was impaired at both the knee and hand in the osteoarthritis group suggests a central phenomenon with deficits in force coding arising from cortical differences between subject groups. This was supported in part by the fact that relative scores for the grip force estimations were lower than those for lower limb estimations at each submaximal force level — a finding which reflects the previously established influence of cutaneous palmer pressure receptors on force coding (Monzee et al., 2003; Wheat et al., 2004). That a deficit was also evident in the grip force estimation tests, where the feedback from palmer cutaneous receptors during grip force estimation was arguably more 'valuable' than that of shin cutaneous receptors during lower limb force estimation, suggests that force estimation acuity is coded primarily by central mechanisms.

If variations in force estimation acuity between groups were the result of cortical differences in force coding then the force estimation ability of osteoarthritis subjects performing knee flexor muscle tests would also be impaired. This was not the case in the current study, casting doubt about whether force estimation differences were centrally generated. Control subjects demonstrated a consistent pattern of impaired force estimation when performing estimation tasks with their knee flexor muscles compared to the osteoarthritis subject group. This pattern was not however evident for the force matching tasks. It is possible that differences in central coding did account for differences in force estimation ability between the subject groups, but the coding difference was the result of chronic changes that had occurred in the periphery; specifically changes in the muscle arising from osteoarthritis induced muscle atrophy. A force estimation difference was evident for the knee extensor task where maximum strength differed between subject groups but not knee flexor tasks where no difference in maximum knee flexor strength was evident.

The major finding of the force matching tasks was a significant difference (p<0.05) in force matching acuity between muscle groups. Regardless of subject group, at lower submaximal force levels, force matching acuity in the knee extensor muscles was significantly greater than that of the knee flexor muscles. Again, it is possible that differences in mechanoreceptor density and location, cortical coding differences and differences in the length tension relationship between muscles may have contributed to the differences in force matching acuity between muscle groups.

Another significant finding (p<0.05) from the force matching tests was the difference in force matching acuity between submaximal force levels, consistent with previously published research on force matching acuity (Jones 1989b; Weerakkody et al., 2003b). Consistent with these two studies, a pattern of overestimation of lower targets and underestimation of higher targets was apparent. Whilst use of a 'relative score' for force matching acuity enabled comparisons across submaximal force levels in the current study, many previous studies have reported and compared absolute errors when investigating force matching acuity, making comparisons difficult in studies that fail to report reference target levels. Jones (1989b) reported force matching overestimations of 44% and 28% at 15% MVC and 25% MVC respectively during contralateral force matching tests in elbow flexor muscles. Jones reported a Weber's fraction of 0.07 for force matching but failed to state whether this value was an average of fractions obtained at multiple submaximal levels or whether it represented the smallest mean Weber's fraction generated. In the Jones study, greatest matching acuity was demonstrated at the 50% MVC target level. In the current study, when observing the 50% MVC matching task, Weber's fractions of 0.10 and 0.07 were obtained from knee extensors and 0.21 and 0.17 for the knee flexors in control and osteoarthritis subjects respectively.

There was a trend towards significance (p=0.066) for the muscle-by-level-by-group interaction, suggesting that the differences in force estimation acuity at the lowest test levels were also evident during force matching tasks but to a lesser extent than those demonstrated during force estimation tasks. This result shows that differences in force estimation, which favour the control group, disappeared during matching tasks.

The major difference between force matching and force estimation protocols was the performance of a reference contraction. Subjects performed the reference contraction with visual and verbal feedback to obtain and maintain the target level of torque output. It is possible that sensory feedback from the reference trial of the matching tests produced a 'performance memory' that overrode the deficit seen in force estimation tasks. How long this performance memory lasted is unknown. Mucha (2002) demonstrated that sensory acuity in a number of sensory modalities (vibration, dynamic and successive two-point discrimination, distance, forms, surface, direction, pressure, weight and position sense) can improve with training. Whilst not specifically investigating force appreciation, Mucha found that the discrimination thresholds for eight of the ten sensory modalities tested significantly improved after 2 weeks of training. The presence of a performance memory in the current study and the findings of Mucha lend indirect support to the notion that force acuity may improve with training.

Control knee extensors

Control knee flexors

OA knee extensors

OA knee flexors
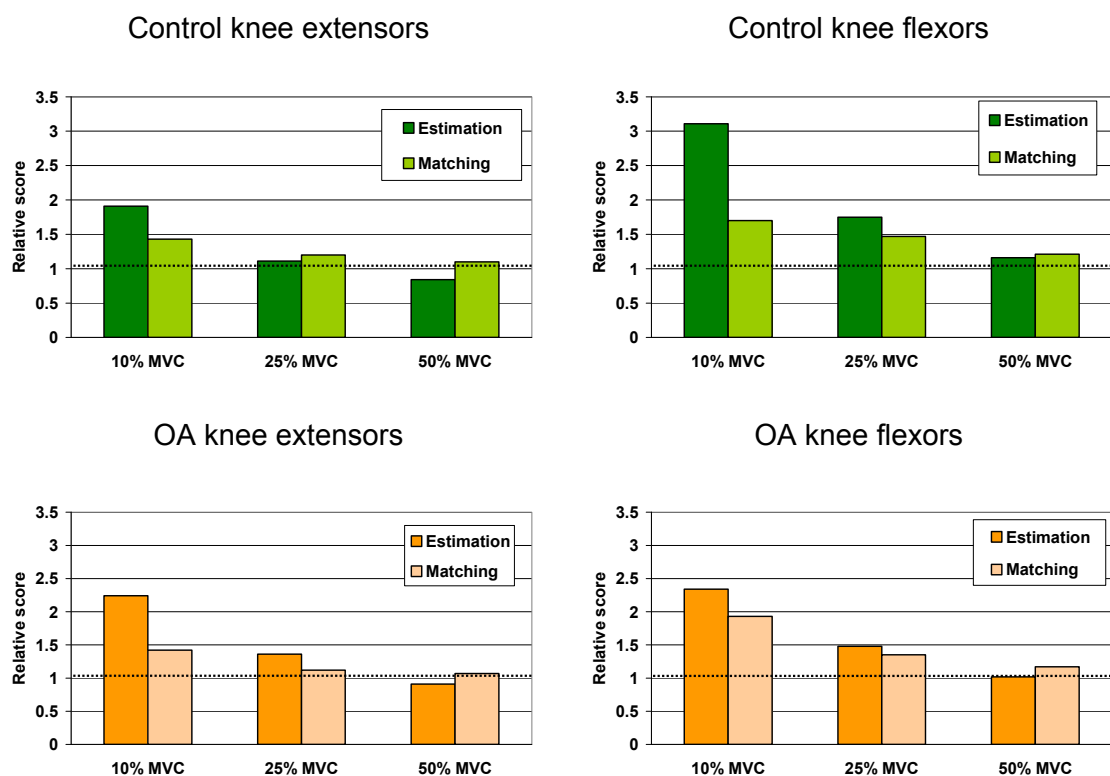
Figure 5.1. Comparison of acuity for estimation and matching tasks

Data are group means. The dashed lines represent perfect force appreciation.

The use of two different tests to measure force appreciation strengthens understandings of force appreciation gained from this study. Force estimation and force matching protocols each elicit unique information about force appreciation. An unexpected finding from the current study may shed light on the way low levels of force generation are coded. As seen in Figure 5.1, marked differences in acuity between force estimation and force matching were evident at the lowest target levels for each muscle in both subject groups. Differences were evident but to a much lesser extent at the other test levels. West et al (2005) contend that force estimation tasks are primarily performed using a 'sense of perceived effort' derived from feedforward coding mechanisms. In contrast, force matching tasks additionally incorporate feedback produced by the peripheral mechanoreceptors activated during reference force production (Jones 1989b; West et al., 2005). The markedly different relative scores obtained from estimation and matching tests for the 10% MVC level in the current study lend strong support to the notion that force coding at very low levels of maximum capacity relies on both centrally and peripherally generated 'force' signals.

The lack of demonstrable difference between groups in force matching at the 10% MVC test level may be a function of degenerative joint changes. It has been reported that joint effusion, oedema and inflammatory mediators can lower the activation thresholds of joint nocioceptors so that 'normal' movement is able to stimulate them (Felson, 2005; Grubb, 2004; Schaible & Grubb, 1993). Therefore it was possible that the lack of significant difference in force matching acuity between groups reflected an augmentation of force coding resulting from increased joint nocioceptor activity. As the pain levels reported by osteoarthritis subjects in current study were not clinically significant and no correlation was identified between pain levels and acuity of force appreciation (a finding mirroring those of Descarreaux et al, 2004), it seems unlikely that joint nocioceptors accounted for the lack of difference in force matching acuity between groups.

McCloskey et al (1974) demonstrated that fatigue influences weight and tension estimation, and Jones and Hunter (1983a, 1983b) established that force sensation is also influenced by muscle fatigue. If fatigue did occur, it would

influence reference and comparison contractions equally as they were performed by the same muscle remembering that target matching values were proportional to maximal capacity. Based on the tendency to scale effort relative to available peak torque, it is possible that the proportion of force matched may have changed between paired trials if fatigue occurred. This would not have affected force estimation trials as only a single trial was conducted at each target level, however the repeated trials for force matching could have been influenced by this effect. Whilst subject fatigue was not specifically monitored in the current study, it is unlikely that muscle fatigue influenced results given that tests were well spaced.

As well as limitations mentioned already, two further factors should be considered. One limitation relates to the influence of cutaneous pressure receptors on force acuity. It is likely that cutaneous pressure receptors underlying the fixation strap on the lower leg were activated during testing. In an effort to minimise this effect, subjects were instructed to concentrate on sensations experienced in the activated muscle and to base matching contractions on these sensations. Subjective feedback at the conclusion of testing suggested this strategy was effective. The effect of cutaneous mechanoreceptor contribution to force coding is a well recognised limitation of force appreciation studies. However, without anaesthetising subjects, it is unlikely that the effect of cutaneous mechanoreceptor input can be neutralised during studies investigating force acuity

Another limitation relates to the grip dynamometer utilised in the current study. The grip test device provided a reading of the maximum force generated during a given contraction level. Any subject overshooting a target level would have been unable to 'correct' their output until the device had been reset. This necessitated a change in test strategy with participants instructed to gradually increase grip pressure until the desired force was produced at which point the contraction ended. Additionally, force output was defined in kilograms with indicator marks spaced at 1 kilogram intervals. Accordingly measures obtained from this device were less precise than those used for lower limb testing. Both groups were tested by the same researcher using identical test strategies, so

any impact of protocol differences and reduced measurement sensitivity will have been experienced by all subjects in the study.

6. SUMMARY AND RECOMMENDATIONS

Osteoarthritis causes considerable pain and dysfunction amongst sufferers. This results in significant social and financial impediments for individuals, their families and communities. Researchers continue to explore the pathogenesis of osteoarthritis and seek methods to prevent the onset of joint degeneration, limit pain and disability and maintain optimum function. Previous osteoarthritis research has considered genetic and environmental influences, bony physiology/pathology, muscle health/function and sensory acuity in osteoarthritic populations. Investigation into sensory acuity in the presence of osteoarthritic changes have revealed changes in both position sense – the ability to detect changes in position - and movement sense – the ability to detect the onset of movement and changes in movement parameters (direction, velocity). However, to date, little work has been done on force sense - the ability to detect and discriminate the level of generated muscle force. The ability to accurately discriminate muscle forces reduces the risk of joint injury arising from inadequate production of muscle forces and arising through excessive compression arising from overproduction of muscle forces.

The purpose of the current study was to investigate force sense in older adults using both force estimation and force matching protocols to establish whether osteoarthritis is associated with deficits in force appreciation. Testing was performed using knee extensor and knee flexor muscle groups as the knee joint is commonly affected by osteoarthritis and causes sufferers considerable pain and disability.

Twenty one healthy older adults with primary osteoarthritis of the knee joint and short-listed for knee joint replacement surgery were evaluated in a single two hour test session. A comparison group comprised of twenty three healthy older adults with no known knee joint pathology also underwent testing. Subjects were positioned in a custom built chair and knee extensor and knee flexor output was measured using a strain gauge connected by strapping to the test leg just above the lateral malleolus. All subjects performed initial testing to determine maximum voluntary capacity for knee extensor and knee flexor muscles of the test leg. Target force levels were derived from individual MVC

with subjects performing force estimation tests at target levels of 10%, 25%, 50% and 75% MVC and force matching tests at target levels of 10%, 25% and 50% MVC. Estimation and matching accuracy was expressed relative to target levels to allow comparisons between test levels, muscles and subject groups. Estimation tests were also conducted at the hand at target levels of 10%, 25% and 50% MVC. Pain and function questionnaires were completed by all subjects and pain and perceived effort were recorded throughout testing.

The results of MVC tests showed that the group with osteoarthritis had significantly lower maximum quadriceps strength compared to their unaffected peers although knee flexor maximum capacity was similar across both groups. Pain and function questionnaires revealed that sufferers of osteoarthritis were considerably affected by their condition. Subjects in the osteoarthritis group experienced significant levels of chronic knee pain and joint stiffness, were less able functionally and reported lower levels of lifestyle activity and exercise participation. There was no difference in ratings of perceived effort between groups during testing and although significant differences in the level of testing-induced pain were recorded, reported pain was very low and did not reach clinically significant levels.

The main findings of the current study were a) force estimation ability but not force matching ability differed across subject groups at lower submaximal test levels; b) force estimation and force matching acuity differed significantly between muscle groups regardless of knee joint health; c) the pattern of poor force appreciation at very high and very low force levels demonstrated in previous studies was evident in both osteoarthritis and control groups and d) differences in (hand) grip force estimation ability were evident across groups.

These findings suggest that force appreciation deficits may be primarily central in origin. A number of factors may have contributed to the force estimation deficits demonstrated by subjects with osteoarthritis. These include changes in muscle fibre type ratios arising from osteoarthritis induced muscle atrophy and possible changes to mechanoreceptor density and firing patterns. Differences in force acuity between muscle groups may be accounted for by considering differences in muscle fibre type ratios and length tension relationships.

6.1 Recommendations for future research

The goal of research into osteoarthritis is to improve the recognition, treatment and prevention of pain and dysfunction arising from this condition. Whilst the current study identified differences in force appreciation acuity between subjects with and without osteoarthritis, further research is needed before these findings will prove beneficial in a clinical setting.

As noted above, the force matching ability of osteoarthritis subjects was similar to that of control subjects, but force estimation acuity was impaired at lower submaximal test levels. This finding suggests that the reference contraction in matching tasks produced a 'performance memory' which in turn effected an improvement in force appreciation for this subject group. Future investigation into the durability of this performance memory, the transferability of this memory to other tasks (e.g. anisometric contractions) and the ability to improve or extend this memory effect is warranted.

Strength training has been shown to improve force control in healthy young adults and individuals with osteoarthritis. Given that exercises to improve muscle strength are a common feature of physiotherapy treatment for osteoarthritis, investigation of the effect of strength training on force estimation and force matching ability is also justified.

Now that force appreciation deficits at low submaximal force levels have been identified, an exploration of the relationship between force appreciation acuity and functional ability may identify activities which demonstrate a greater reliance on good force appreciation. As research establishes whether force appreciation is 'trainable', improvements in function may be facilitated by improving force appreciation ability.

Force appreciation deficits have been demonstrated within an osteoarthritis population in the current study; however the study's design was unable to determine the causality and progression of these deficits. As there is evidence to suggest that force appreciation ability varies considerably in healthy populations (Cafarelli, 1988; Cafarelli & Bigland-Ritchie, 1979; Cafarelli &

Kostka, 1981; Carson et al., 2002; Jones & Hunter, 1982) a prospective study observing a group of healthy young individuals with poor force appreciation for the incidence of degenerative joint changes may provide useful insights regarding the pathogenesis of osteoarthritis. Likewise investigating force appreciation in individuals before and after lower limb injury and investigating the downstream incidence of joint degeneration may prove useful.

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8. APPENDICES

Appendix 1: Northern X Regional Ethics Committee Approval Notification

<table>
<tr>
<td>

**Health
and
Disability
Ethics
Committees**

e-mail: pat_chainey@moh.govt.nz

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Northern X Regional Ethics Committee
Ministry of Health
3rd Floor, Unisys Building
650 Great South Road, Penrose
Private Bag 92 522
Wellesley Street, Auckland
Phone (09) 580 9105
Fax (09) 580 9001

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22 December 2005.

Ms Helen Brereton
State Highway 14
RD 9
Whangarei.

Dear Helen

NTX/05/11/147   **Acuity of force appreciation in adults with osteoarthritis of the knee joint:**

Principal Researcher: Ms Helen Brereton, Auckland University of Technology/Whangarei Hospital.
Supervisor: Prof. Peter McNair, Auckland University of Technology.

Thank you for answering the concerns of the Committee.

The above study has been given ethical approval by Northern X Ethics Committee for the Northern Region. A list of members of this Committee is attached.

Approved Documents:
- Information Sheet/Consent Form V#2, dated 13 November 2005.
- Poster V#2, December 2005.

Certification
The Committee is satisfied that this study is not being conducted principally for the benefit of the manufacturer or distributor and may be considered for coverage under ACC.

Accreditation
This Committee involved in the approval of this study is approved by the Health Research Council and is constituted and operates in accordance with the Operational Standard for Ethics Committees, March 2002.

Progress Reports
The study is approved until 22 December 2006 (to cover writing up and reporting) A progress report is required for this study by 22 December 2006.

A form should come off our database requesting this information two months prior to the review date but if a form is not received, it is still your responsibility to provide a progress report and this may be obtained from the website below. Please note that failure to complete and return this form may result in the withdrawal of ethical approval.

..../2

Administered by the Ministry of Health   Approved by the Health Research Council   http://www.newhealth.govt.nz/ethicscommittees

Please advise the Committee when the study is completed and under the ethical approval process, a final report is also <u>required</u> at the conclusion of the study.

Requirements for SAE Reporting
Please advise the Committee as soon as possible on the SAE form to be found on the website below, if there are any serious adverse events that may relate to this study.
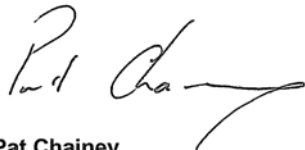
Amendments:
All amendments to the study must be advised to the Committee prior to their implementation, except in the case where immediate implementation is required for reasons of safety. In such cases the Committee must be notified as soon as possible of the change.

Please quote the above ethics committee reference number in all correspondence.

It should be noted that Ethics Committee approval does not imply any resource commitment or administrative facilitation by any healthcare provider, within whose facility the research is to be carried out. Where applicable, authority for this must be obtained separately from the appropriate manager within the organisation.

Yours sincerely,

Pat Chainey
Administrator, Northern X Committee

Cc: Northland DHB.

Appendix 2: Absolute error, relative error and relative score

Sensory acuity can be quantified using discrimination or matching tasks. During discrimination tasks, individuals are exposed to reference and comparison sensory events that differ only in one variable (e.g. volume, pitch, weight, brightness, tension). The individual is asked to determine whether reference and comparison events are equal (e.g. lesser, greater or equivalent pressure). In a matching task, individuals produce a comparison effort that reproduces a reference event (e.g. matching forces, matching position).

The degree of approximation between the reference value (R) and comparison estimate (C) is usually reported using 'error' measures. Two commonly reported errors are the absolute error and the relative error. The 'x' used in the formulas below represents the units used to test the sensory modality under investigation (e.g. kilograms, decibels, Newtons).

	Symbol	Equation	Unit	Synonyms
Absolute error	**Δx**	**Δx = Rx – Cx**	**as per x**	**error, limen**

Note: This measure limits useful comparisons between sensory modalities (e.g. movement versus force); between sensory apparatus (e.g. light touch, fingertips versus shin); and across the sensory continuum (low levels of force versus high levels of force). Unless indicated with +/- signs, directionality of error (too low, too high) is not always clear.

	Symbol	Equation	Unit	Synonyms
Relative error	**δx**	$\delta x = \dfrac{Rx - Cx}{Rx}$	**nil**	**Weber's fraction**

Note: Relative errors are ratios, and have no units. This overcomes the first three absolute error limitations listed above. However, error direction is generally not apparent from published relative error values. 'Percentage error' is the relative error times 100.

To provide an error measure that indicates directionality, this thesis uses a measure which has been labelled 'relative score'. The formula is as follows

Relative score = RS = $\dfrac{Cx}{Rx}$

Perfect matching is indicated by a score of 1.0. A relative score below 1.0 indicates comparison values were less than reference values, with relative scores above 1.0 indicating that comparison values exceeded reference targets.

(See Williams et al., 1984; Jones, 1989b; and West et al., 2005 for examples of studies using absolute error (difference limen), relative error (Weber's fraction) and relative score respectively.)

Appendix 3: Priority scoring system for knee joint replacement

Pain (40%)			Points
Degree	•	None	0
	•	Mild, slight or occasional pain. Patient has not altered patterns of activity or work.	4
	•	Mild-moderate or frequent pain. Patient has not altered patterns of activity or work.	6
	•	Moderate. Patient is active but has modified or given up some activities because of pain.	9
	•	Moderate-severe or fairly severe pain with substantial limitation of activities.	14
	•	Severe, major pain and serious limitation.	20
Patient must be on maximum medical therapy at the time of rating.			
Occurrence	•	None or with first steps only.	0
	•	Only after long walks (30 mins).	4
	•	With all walking; mostly day pain.	10
	•	Significant, regular night pain.	20

Functional Activity (20%)			Points
Time walked	•	Unlimited	0
	•	31–60 minutes (e.g. longer shopping trips to mall)	2
	•	11–30 minutes (e.g. gardening, grocery shopping)	4
	•	2–10 minutes (e.g. trip to letter box)	6
	•	Under 2 minutes or indoors only (housebound)	10
	•	Unable to walk	10
Other functional limitations*	•	None	0
	•	Mild	2
	•	Moderate	4
	•	Severe	10
For example: putting on shoes, managing stairs, sitting to standing, sexual activity, recreation or hobbies, walking aids needed.			

Movement and Deformity (20%)			Points
Pain on examination*	•	None	0
	•	Mild	4
	•	Moderate	6
	•	Severe	10
Overall results of both active and passive range of motion.			
Other abnormal findings*	•	None	0
	•	Mild	4
	•	Moderate	6
	•	Severe	10
Limited to orthopaedic problems e.g. reduced range of motion, deformity, limp, instability, progressive X-ray findings.			

Other Factors (20%)		Points
Multiple joint involvement	• No, single joint	0
	• Yes, each affected joint mild-moderate severity	4
	• Yes, severe involvement (e.g. severe rheumatoid arthritis)	10
Ability to work, care for dependents, live independently*	• Not threatened or difficult	0
	• Not threatened but more difficult	4
	• Threatened but not more difficult	6
	• Immediately threatened	10
Difficulty must be related to affected joint.		

(Coleman, McChesney & Twaddle, 2005; New Zealand Ministry of Health, 2007)

Appendix 4: Information Sheet

INFORMATION SHEET

Acuity of Force Appreciation in the Knee Joint

Principal investigator:
Helen Brereton Dip Phty, MNZSP
Whangarei Hospital
Private Bag 742, Whangarei
Ph: 4384384 or 0211247877

Supervising Investigator:
Peter J. McNair PhD MNZSP
Professor, Faculty of Health Studies
Auckland University of Technology
Private Bag 92006, Auckland
Ph. 307-9999 Ext. 7143

Date: _____

You are invited to take part in the following study which is being undertaken by the School of Physiotherapy, Auckland University of Technology and the Physiotherapy Department at Whangarei Hospital. This information sheet explains the study to you, and you can then decide whether you would like to be involved. If you do not understand any aspect of the study described below, please ask for clarification.

Participating in this study is entirely your choice, and if you do agree to take part, you are free to withdraw from the study at any time without having to give a reason. This will not affect your future care or treatment in any way. You do not have to decide immediately about participating in the study. We would ask that you notify us of your decision within 5 days of the date of this notice (see above).

This study will be undertaken at the Whangarei Hospital Physiotherapy Gymnasium, Maunu Rd, Whangarei.

Purpose of the study

Research continues to identify the causes and consequences of osteoarthritis in the knee joint. It has been shown that people with arthritis in the knee have more difficulty feeling movement in their affected knees than people with healthy knees. This means that arthritis sufferers take longer to detect when movement occurs in the knee joint. They are also less accurate when duplicating movement patterns. It is unknown whether this loss of movement awareness is matched by deterioration in the awareness of forces produced by muscles that move the knee joint.

It is the purpose of this study to investigate whether arthritis sufferers are able to effectively perceive the forces their muscles produce. This will be tested by asking volunteers to match as accurately as possible different muscle forces in the quadriceps muscles of both healthy and affected legs. Testing will also be done using a grip strength tester to see whether any differences in force matching accuracy are specific to the injured limb or generalized through the whole body.

Selection of participants

This study will involve volunteers who meet the following criteria:

- a primary diagnosis of osteoarthritis in one knee

This study will involve other volunteers with no osteoarthritis to allow comparisons to be made in people with and without osteoarthritis.

You may not be included if:

- you have had two total knee joint replacements
- you have severe osteoarthritis of the hip joints or any right arm impairment
- you have rheumatoid arthritis
- you have a history of uncontrolled hypertension
- you have a history of unstable angina
- you have a history of cerebral ischemia (stroke)
- you have a recent or long standing history of sensation changes in your limbs
- you have received physiotherapy treatment in the past 3 months.
- you have medical conditions that could place you at risk of harm if involved in this study

What does the study involve?

All participants will undertake one session of testing. At this session, you will be asked to perform a series of tests to measure the strength of your knee muscles in both your legs and the grip strength in your right hand. You will be asked to estimate and match the forces you produce with your muscles. Leg muscles will be tested in sitting, with participants pushing against a resisted cuff. The testing of hand muscles will be performed using a grip strength testing device. Testing will take no more that 2 hours.

You will also be asked to complete questionnaires that provide information on the extent of pain and disability resulting from your arthritis. Assistance will be given to enable completion of the forms by the principal investigator if you request it. You are free to not answer any questions which make you feel uncomfortable.

The data collected may be used for follow up studies after the main study has been completed. If that should be considered, you will be contacted again at a later date regarding participation in any further study. However being involved in this study does not mean you are obliged to take part in any further studies.

If you have any questions though out or following your participation in the study, the principal investigator, Helen Brereton can be contacted (my contact details are at the top of the first page).

Benefits, discomforts and risks

Benefits: This study comprises of simple measures of muscle force awareness, and does not involve the application of any arthritis treatment techniques. However, if significant muscle weakness is noticed during testing, you will be given a report to submit to your doctor and you will be given the option of attending physiotherapy for remedial strengthening exercises.

Discomforts and physical risks: The tests and exercises requiring maximum effort may elicit discomfort in your knee joint. If you are unaccustomed to exercise, you may experience some minor muscle pain after the testing session.

To minimize the risks:
- As part of testing, you will undertake a short standardized warm-up that will include low intensity exercise prior to the maximal effort tests.
- You will be provided with an information sheet describing how to manage any discomfort you may have after testing.
- The assessor in charge of testing is a senior physiotherapist who will have access to treatment modalities normally used to treat these symptoms.

Compensation

In the unlikely event of a physical injury as a result of your participation in this study, you may be covered by ACC under the Injury Prevention, Rehabilitation and Compensation Act. ACC cover is not automatic and your case will need to be assessed by ACC according to the provisions of the 2002 Injury Prevention Rehabilitation and Compensation Act. If your claim is accepted by ACC, you still might not get any compensation. This depends on a number of factors such as whether you are an earner or non-earner. ACC usually provides only partial reimbursement of costs and expenses and there may be no lump sum compensation payable. There is no cover for mental injury unless it is a result of physical injury. If you have ACC cover, generally this will affect your right to sue the investigators.

If you have any questions about ACC, contact your nearest ACC office (4377800) or the principal investigator.

Confidentiality

No material that could personally identify you will be used in any reports on this study unless your personal approval is given for the distribution of results to specific persons (eg your doctor). All subjects will be assigned a number and only the principal researcher and her supervisor will have access to your name. All subject records will be locked away under lock and key by the principal researcher.

If you wish to have a copy of the results of this research, you are entitled to this on request from Helen Brereton. These will be available after the study is completed and published. You are advised however that a significant delay may occur between testing and the publication of the results.

Finally

This study has received ethical approval from the Northern X Regional Ethics Committee.

If you agree to participate in the study, please complete the attached consent form.

If you have any queries or concerns regarding your rights as a participant in this research, you may contact a Health and Disability Advocate, telephone number 0800 555 050 (Northland to Franklin).

Appendix 5: Physical Activity Readiness Questionnaire

PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (PARQ)

Acuity of Force Appreciation in the Knee Joint

Yes No

☐ ☐ Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?

_____

☐ ☐ Do you feel pain in your chest when you do physical activity?

_____

☐ ☐ In the past month, have you had chest pain when you were not doing physical activity?

_____

☐ ☐ Do you lose your balance because of dizziness or do you ever lose consciousness?

_____

☐ ☐ Do you have a bone or joint problem that could be made worse by a change in physical activity?

_____

☐ ☐ Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?

_____

☐ ☐ Do you know of any other reason why you should not do physical activity?

_____

Appendix 6: Health Screening Questionnaire

SCREENING QUESTIONNAIRE
Acuity of Force Appreciation in the Knee Joint

---

1. Is your general health good? ☐ Yes ☐ No

    If no, what problems do you have?_____

2. Are you currently taking any medication? ☐ Yes ☐ No

    If yes, please specify:_____

3. Have you had any physiotherapy in the past 3 months? ☐ Yes ☐ No

    If yes, please specify (e.g. what for?):_____

4. Do you have any current disease or illness ☐ Yes ☐ No

    If yes, please specify (e.g. where?):_____

5. Do you have uncontrolled high or low blood pressure? ☐ Yes ☐ No

6. Do you have a heart condition? ☐ Yes ☐ No

7. Have you ever had a stroke? ☐ Yes ☐ No

8. Do you have uncontrolled epilepsy? ☐ Yes ☐ No

9. Do you have open wounds / skin conditions on your legs? ☐ Yes ☐ No

    If yes, please specify:_____

11. Do you have osteoarthritis in either knee? ☐ Yes ☐ No

    If yes, please specify which knee: _____

12. Have you ever had a joint replacement? ☐ Yes ☐ No

    If yes, please specify which joint(s):_____

Thank you for completing this questionnaire.

Appendix 7: Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC V3.1)

WOMAC V3.1
Acuity of Force Appreciation in the Knee Joint

Your Full Name:_____ Today's Date: ____/_____/_____

1. The following questions concern the amount of pain you are currently experiencing in your knees. For each situation, please enter the amount of pain you have experienced in the past 48 hours.

		None	Mild	Moderate	Severe	Extreme
A. Walking on a flat surface	A.	0	1	2	3	4
B. Going up or down stairs	B.	0	1	2	3	4
C. At night while in bed	C.	0	1	2	3	4
D. Sitting or lying	D.	0	1	2	3	4
E. Standing upright	E.	0	1	2	3	4

2.

	None	Mild	Moderate	Severe	Extreme
A How severe is your stiffness after first awakening in the morning?	0	1	2	3	4
B How severe is your stiffness after sitting, lying, or resting later in the day?	0	1	2	3	4

3. 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 48 hours, in your knees. What degree of difficulty do you have with?

		None	Mild	Moderate	Severe	Extreme
A	Descending (going down) stairs	0	1	2	3	4
B	Ascending (going up) stairs	0	1	2	3	4
C	Rising from sitting	0	1	2	3	4
D	Standing	0	1	2	3	4
E	Bending to floor	0	1	2	3	4
F	Walking on a flat surface	0	1	2	3	4
G	Getting in/out of car	0	1	2	3	4
H	Going shopping	0	1	2	3	4
I	Putting on socks/stockings	0	1	2	3	4
J	Rising from bed	0	1	2	3	4
K	Taking off socks/stockings	0	1	2	3	4
L	Lying in bed	0	1	2	3	4
M	Getting in/out of bath	0	1	2	3	4
N	Sitting	0	1	2	3	4
O	Getting on/off toilet	0	1	2	3	4
P	Heavy domestic duties (mowing the lawn, lifting heavy grocery bags)	0	1	2	3	4
Q	Light domestic duties (such as tidying a room, dusting, cooking)	0	1	2	3	4

Appendix 8: Community Healthy Activities Model Program for Seniors Physical Activity Questionnaire (CHAMPS)

CHAMPS Activity Questionnaire for Older Adults
Acuity of Force Appreciation in the Knee Joint

Patient   Date

This questionnaire is about activities that you may have done in the past 4 weeks. The questions on the following pages are similar to the example shown below.

INSTRUCTIONS

If you DID the activity in the past 4 weeks:

Step #1   Check the YES box.

Step #2   Think about how many TIMES a week you usually did it, and write your response in the space provided.

Step #3   Circle how many TOTAL HOURS in a typical week you did the activity.

Here is an example of how Mrs. Jones would answer question #1: Mrs. Jones usually visits her friends Maria and Olga twice a week. She usually spends one hour on Monday with Maria and two hours on Wednesday with Olga. Therefore, the total hours a week that she visits with friends is 3 hours a week.

In a typical week during the past 4 weeks, did you…								
1. Visit with friends or family (other than those you live with)? ☒ YES How many TIMES a week? **2** ➔ ☐ NO	How many TOTAL hours a week did you usually do it? ➔	Less than 1 hour	1-2½ hours	(3-4½ hours)	5-6½ hours	7-8½ hours	9 or more hours

If you DID NOT do the activity:

• Check the NO box and move to the next question

In a typical week during the past 4 weeks, did you …							
1. Visit with friends or family (other than those you live with)? ☐ **YES** How many TIMES a week?_____ ➔ ☐ **NO**	How many TOTAL <u>hours a week</u> did you usually do it? ➔	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
2. Go to the senior center? ☐ **YES** How many TIMES a week?_____ ➔ ☐ **NO**	How many TOTAL <u>hours a week</u> did you usually do it? ➔	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
3. Do volunteer work? ☐ **YES** How many TIMES a week?_____ ➔ ☐ **NO**	How many TOTAL <u>hours a week</u> did you usually do it? ➔	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
4. Attend church or take part in church activities? ☐ **YES** How many TIMES a week?_____ ➔ ☐ **NO**	How many TOTAL <u>hours a week</u> did you usually do it? ➔	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
5. Attend other club or group meetings? ☐ **YES** How many TIMES a week?_____ ➔ ☐ **NO**	How many TOTAL <u>hours a week</u> did you usually do it? ➔	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
6. Use a computer? ☐ **YES** How many TIMES a week?_____ ➔ ☐ **NO**	How many TOTAL <u>hours a week</u> did you usually do it? ➔	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
7. Dance (such as square, folk, line, ballroom) (do <u>not</u> count aerobic dance here)? ☐ **YES** How many TIMES a week?_____ ➔ ☐ **NO**	How many TOTAL <u>hours a week</u> did you usually do it? ➔	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours

3

In a typical week during the past 4 weeks, did you …							
8. Do woodworking, needlework, drawing, or other arts or crafts? ☐ **YES** How many TIMES a week?_____ ➔ ☐ **NO**	How many TOTAL <u>hours a week</u> did you usually do it? ➔	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
9. Play golf, carrying or pulling your equipment (count <u>walking time</u> only)? ☐ **YES** How many TIMES a week?_____ ➔ ☐ **NO**	How many TOTAL <u>hours a week</u> did you usually do it? ➔	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
10. Play golf, riding a cart (count <u>walking time</u> only)? ☐ **YES** How many TIMES a week?_____ ➔ ☐ **NO**	How many TOTAL <u>hours a week</u> did you usually do it? ➔	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
11. Attend a concert, movie, lecture, or sport event? ☐ **YES** How many TIMES a week?_____ ➔ ☐ **NO**	How many TOTAL <u>hours a week</u> did you usually do it? ➔	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
12. Play cards, bingo, or board games with other people? ☐ **YES** How many TIMES a week?_____ ➔ ☐ **NO**	How many TOTAL <u>hours a week</u> did you usually do it? ➔	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
13. Shoot pool or billiards? ☐ **YES** How many TIMES a week?_____ ➔ ☐ **NO**	How many TOTAL <u>hours a week</u> did you usually do it? ➔	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours

In a typical week during the past 4 weeks, did you …

Question		Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
14. Play singles tennis (do not count doubles)? ☐ YES How many TIMES a week?_____ ➜ ☐ NO	How many TOTAL hours a week did you usually do it? ➜	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
15. Play doubles tennis (do not count singles)? ☐ YES How many TIMES a week?_____ ➜ ☐ NO	How many TOTAL hours a week did you usually do it? ➜	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
16. Skate (ice, roller, in-line)? ☐ YES How many TIMES a week?_____ ➜ ☐ NO	How many TOTAL hours a week did you usually do it? ➜	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
17. Play a musical instrument? ☐ YES How many TIMES a week?_____ ➜ ☐ NO	How many TOTAL hours a week did you usually do it? ➜	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
18. Read? ☐ YES How many TIMES a week?_____ ➜ ☐ NO	How many TOTAL hours a week did you usually do it? ➜	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
19. Do heavy work around the house (such as washing windows, cleaning gutters)? ☐ YES How many TIMES a week?_____ ➜ ☐ NO	How many TOTAL hours a week did you usually do it? ➜	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
20. Do light work around the house (such as sweeping or vacuuming)? ☐ YES How many TIMES a week?_____ ➜ ☐ NO	How many TOTAL hours a week did you usually do it? ➜	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours

In a typical week during the past 4 weeks, did you …

Question		Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
21. Do heavy gardening (such as spading, raking)? ☐ YES How many TIMES a week?_____ ➜ ☐ NO	How many TOTAL hours a week did you usually do it? ➜	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
22. Do light gardening (such as watering plants)? ☐ YES How many TIMES a week?_____ ➜ ☐ NO	How many TOTAL hours a week did you usually do it? ➜	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
23. Work on your car, truck, lawn mower, or other machinery? ☐ YES How many TIMES a week?_____ ➜ ☐ NO	How many TOTAL hours a week did you usually do it? ➜	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours

**Please note: For the following questions about running and walking, include use of a treadmill.

Question		Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
24. Jog or run? ☐ YES How many TIMES a week?_____ ➜ ☐ NO	How many TOTAL hours a week did you usually do it? ➜	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
25. Walk uphill or hike uphill (count only uphill part)? ☐ YES How many TIMES a week?_____ ➜ ☐ NO	How many TOTAL hours a week did you usually do it? ➜	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
26. Walk fast or briskly for exercise (do not count walking leisurely or uphill)? ☐ YES How many TIMES a week?_____ ➜ ☐ NO	How many TOTAL hours a week did you usually do it? ➜	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours

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Question		Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
27. Walk to do errands (such as to/from a store or to take children to school (count walk time only)? ☐ YES How many TIMES a week?_____ ➔ ☐ NO	How many TOTAL hours a week did you usually do it? ➔						
28. Walk leisurely for exercise or pleasure? ☐ YES How many TIMES a week?_____ ➔ ☐ NO	How many TOTAL hours a week did you usually do it? ➔						
29. Ride a bicycle or stationary cycle? ☐ YES How many TIMES a week?_____ ➔ ☐ NO	How many TOTAL hours a week did you usually do it? ➔						
30. Do other aerobic machines such as rowing, or step machines (do not count treadmill or stationary cycle)? ☐ YES How many TIMES a week?_____ ➔ ☐ NO	How many TOTAL hours a week did you usually do it? ➔						
31. Do water exercises (do not count other swimming)? ☐ YES How many TIMES a week?_____ ➔ ☐ NO	How many TOTAL hours a week did you usually do it? ➔						
32. Swim moderately or fast? ☐ YES How many TIMES a week?_____ ➔ ☐ NO	How many TOTAL hours a week did you usually do it? ➔						
33. Swim gently? ☐ YES How many TIMES a week?_____ ➔ ☐ NO	How many TOTAL hours a week did you usually do it? ➔						

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Question		Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
34. Do stretching or flexibility exercises (do not count yoga or Tai-chi)? ☐ YES How many TIMES a week?_____ ➔ ☐ NO	How many TOTAL hours a week did you usually do it? ➔						
35. Do yoga or Tai-chi? ☐ YES How many TIMES a week?_____ ➔ ☐ NO	How many TOTAL hours a week did you usually do it? ➔						
36. Do aerobics or aerobic dancing? ☐ YES How many TIMES a week?_____ ➔ ☐ NO	How many TOTAL hours a week did you usually do it? ➔						
37. Do moderate to heavy strength training (such as hand-held weights of more than 5 lbs., weight machines, or push-ups)? ☐ YES How many TIMES a week?_____ ➔ ☐ NO	How many TOTAL hours a week did you usually do it? ➔						
38. Do light strength training (such as hand-held weights of 5 lbs. or less or elastic bands)? ☐ YES How many TIMES a week?_____ ➔ ☐ NO	How many TOTAL hours a week did you usually do it? ➔						
39. Do general conditioning exercises, such as light calisthenics or chair exercises (do not count strength training)? ☐ YES How many TIMES a week?_____ ➔ ☐ NO	How many TOTAL hours a week did you usually do it? ➔						

In a typical week during the past 4 weeks, did you …		Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
40. Play basketball, soccer, or racquetball (do not count time on sidelines)? ☐ YES How many TIMES a week?_____ ➔ ☐ NO	How many TOTAL hours a week did you usually do it? ➔	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours
41. Do other types of physical activity not previously mentioned (please specify)? _____ ☐ YES How many TIMES a week?_____ ➔ ☐ NO	How many TOTAL hours a week did you usually do it? ➔	Less than 1 hour	1-2½ hours	3-4½ hours	5-6½ hours	7-8½ hours	9 or more hours

Thank You

Appendix 9: Lower Limb Task Questionnaire

Lower Limb Task Questionnaire
Acuity of Force Appreciation in the Knee Joint

FUNCTION

Patient: _____ Date:_____

Please rate your ability to do the following activities in the past 24 hours by circling the number below the appropriate response. If you did not have the opportunity to perform an activity in the past 24 hours, please make your best estimate on which response would be the most accurate.

Please rate the degree of difficulty you experience doing the following tasks according to the following scale:
- 0. = No difficulty
- 1. = Mild difficulty
- 2. = Moderate difficulty
- 3. = Severe difficulty
- 4. = Unable

Please rate how important each task is to you in your daily life according to the following scale:
- 1. = Not important
- 2. = Mildly important
- 3. = Moderately important
- 4. = Very important

Please answer all questions. DIFFICULTY IMPORTANCE

Activities of daily living

		DIFFICULTY	IMPORTANCE
1.	Walk for 10 minutes	0 1 2 3 4	1 2 3 4
2.	Walk up or down 10 steps (1 flight)	0 1 2 3 4	1 2 3 4
3.	Stand for 10 minutes	0 1 2 3 4	1 2 3 4
4.	Stand for a typical work day	0 1 2 3 4	1 2 3 4
5.	Get on and off a bus	0 1 2 3 4	1 2 3 4
6.	Get up from a lounge chair	0 1 2 3 4	1 2 3 4
7.	Push or pull a heavy trolley	0 1 2 3 4	1 2 3 4
8.	Get in and out of a car	0 1 2 3 4	1 2 3 4
9.	Get out of bed in the morning	0 1 2 3 4	1 2 3 4
10.	Walk across a slope	0 1 2 3 4	1 2 3 4

Recreational activities

		DIFFICULTY	IMPORTANCE
1.	Jog for 10 minutes	0 1 2 3 4	1 2 3 4
2.	Pivot or twist quickly while walking	0 1 2 3 4	1 2 3 4
3.	Jump for distance	0 1 2 3 4	1 2 3 4
4.	Run fast/sprint	0 1 2 3 4	1 2 3 4
5.	Stop and start quickly	0 1 2 3 4	1 2 3 4
6.	Jump upwards and land	0 1 2 3 4	1 2 3 4
7.	Kick a ball hard	0 1 2 3 4	1 2 3 4
8.	Pivot or twist quickly while running	0 1 2 3 4	1 2 3 4
9.	Kneel on both knees for 5 minutes	0 1 2 3 4	1 2 3 4
10.	Squat to the ground / floor	0 1 2 3 4	1 2 3 4

Appendix 10: Consent Form

Acuity of force appreciation in the osteoarthritic knee joint.

REQUEST FOR INTERPRETER			
English	I wish to have an interpreter.	Yes	No
Maori	E hiahia ana ahau ki tetahi kaiwhakamaori/kaiwhaka pakeha korero.	Ae	Kao
Samoan	Oute mana'o ia iai se fa'amatala upu.	Ioe	Leai
Tongan	Oku ou fiema'u ha fakatonulea.	Io	Ikai
Cook Island	Ka inangaro au i tetai tangata uri reo.	Ae	Kare
Niuean	Fia manako au ke fakaaoga e taha tagata fakahokohoko kupu.	E	Nakai
Fijian	Au gadreva me dua e vakadewa vosa vei au	Io	Sega
Tokelaun	Ko au e fofou ki he tino ke fakaliliu te gagana Peletania ki na gagana o na motu o te Pahefika	Ioe	Leai

Principal investigator:
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Ph: 4384384 or 0211247877

Supervising Investigator:
Peter J. McNair PhD MNZSP
Professor, Faculty of Health Studies
Auckland University of Technology
Private Bag 92006, Auckland
Ph. 307-9999 Ext. 7143

This project has been explained to me by _____ who is

the _____ for this study.

I have read and I understand the information sheet (dated   /   /   ) for volunteers taking part in this study designed to measure muscle force awareness.
I have had the opportunity to discuss this study. I am satisfied with answers I have been given.
I have had the opportunity to use whanau support or a friend to help me ask questions and understand the study.
I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time and this will in no way affect my continuing health care.
I understand that my participation in this study is confidential and that no material which could identify me will be used in any reports on this study.
I understand the treatment, or investigation, will be stopped if it should appear harmful to me.
I understand the compensation provisions for this study.
I have had time to consider whether to take part.
I know who to contact if I have any side effects to the study.
I know who to contact if I have any questions about the study.

I agree with all the statements listed above and I _____ (full name) hereby consent to take part in this study.

Signature:_____ Date:_____

I wish to have a copy of the results.   YES/NO

I agree to my GP being informed of the results of my participation in this study if significant muscle weakness is found during the testing process.   YES/NO

Appendix 11: Summary-of-results letter sent to study participants.

<div style="border:1px solid; background:#aee3f7; padding:1em;">

Acuity of force appreciation in the osteoarthritic knee joint.

AUT
AUCKLAND UNIVERSITY OF TECHNOLOGY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

</div>

Dear   February, 2007.

Thankyou again for your participation in this study. As you know, this was a study looking at how well people judge the amount of force their muscle is producing during activity. Specifically I wanted to investigate whether the 'force judging' ability of people with arthritis in their knee joint was different from that of people with healthy knee joints.

All in all, 44 people were tested, 12 women and 11 men with healthy knees and 9 men and 12 women with osteoarthritis in their knees. Two of the osteoarthritis group were tested twice (both knees had arthritis) giving at least 10 people in each group which is a fantastic sample size given this type of study, so thankyou again!

Before I explain the results, I thought you might like to know a bit of background information on the way our body works out how much muscle force it is producing. It may seem a little bit technical but I have included an example later on which will make everything much clearer! There are two main mechanisms. The first mechanism uses sensation from the muscle itself to create a mental picture of activity in the muscle. Specialised nerve endings in the muscle react when our muscle tenses and contracts. Nerve endings in the joint and skin also contribute if they are moved or compressed by the muscle action. These nerve endings relay information to various parts of the brain about how much tension is being produced at any given time. This is commonly called sensory *feedback* because the information is gathered as a result of muscle activity. The other mechanism we use to work out muscle forces is quite surprising, but it is very effective. Whenever we activate a muscle, the brain message sent to turn on the muscle is recorded by other parts of the brain. This is then scrutinised to get an appreciation of how hard the muscle is working. This is called a *feedforward* strategy because the information is gathered before the muscle is active. It appears that the brain has many different lines of data it can use to measure or 'code' force. These data sources overlap each other so that loss of one source does not necessarily affect how well we measure forces. This is demonstrated by those people who have had a hip or knee joint replacement. Even though the joint nerve endings are removed along with the damaged bone ends, people with joint replacements can still display reasonable movement and force control. It does seem however, from most of the research done so far, that the brain pays more attention to the feedforward mechanisms when coding force.

The following example explains how these two mechanisms work. You want to lift your coffee cup to your mouth. Your brain phones your elbow muscles and tells them to get busy. The loudness of the message dictates the amount of force needed; for example, it will whisper if only a little bit of force is needed because your coffee cup is so full it might spill over. Other parts of the brain 'tap' the phone line and record what your brain says and specifically, how loudly it says it. From this 'recording' the brain is able to determine how hard the elbow muscle is working. At the same time, the message has gone to the elbow muscles and now an 'echo' comes back along the phone line. The size of the echo also gives the brain information about how hard the muscle is working.

Now that you better understand these two main mechanisms, I can reveal the interesting findings from our study. The osteoarthritis group; overall had weaker quadriceps muscles (used for the 'pushing' tests) which is exactly what you would expect. Interestingly, force coding by the hamstrings muscle (used for the 'pulling' tests) was a lot less accurate than that of the quadriceps muscles regardless of the health of your knees.

In terms of force coding, there was no difference between the two groups at the 25, 50 and 75 percent levels in any of the tests. Now don't be disappointed because the exciting finding was *that there was a difference at the 10% level*. This is interesting because it reveals that the brain can't only rely on feedforward data for the really low levels of muscle activity. There just isn't enough information for the brain to get an accurate 'picture' of muscle force. At these levels, it needs 'feedback' from the nerve endings in the muscles, joints and skin.

This is fascinating for two reasons; most of the time we only use a small percentage of our total strength to perform routine activities, and other studies have shown that our sensation can be trained and improved. Muscles have an important role in protecting joints. When they cause a joint to bend in one direction they also 'stiffen' the opposite side so the joint moves steadily and smoothly– for example, thigh muscles contract to stiffen the knee joint when we take weight on our leg. Without this effect it would be like trying to use chopsticks to turn chops on the barbeque instead of tongs! As we potter about, we generally use low levels of force to do the task we need. Because force coding and therefore muscle control is limited at lower force levels in people with arthritis, it may be that osteoarthritic joints are less protected than healthy joints during gentle activity. The joints may not stiffen enough, or conversely, muscles may exert too much stiffening pressure and compress the joint surfaces harder than needed. Either way, 'not enough' and 'too much' force has the potential to aggravate damaged knee joints, especially if they are already inflamed and sore.

The good news is that our sensation can be trained. Other studies have shown that people can improve their sense of movement and balance as well as their ability to discriminate pressure and weight differences. Additionally similar studies have shown that the ability to control forces can improve with exercise.

When evidence of force coding deficits is combined with the ability to retrain sensation, these results have potential to help prevent and reduce some of the pain and dysfunction associated with osteoarthritis. It may well be that 'force' training exercises are included in rehabilitation programmes in the future. Of course further research needs to be done to find the best training techniques to improve force coding.

So *thank you* again for your assistance, and your contribution to science. If you have any further queries about the results of this study, don't hesitate to contact me at 4384384 or care of the Physiotherapy Department at Whangarei Hospital (4304101 ext 7525).

Kind regards

Helen Brereton