FACTORS AFFECTING PERCEIVED EXERTION AND TASK DURATION DURING INTERMITTENT ISOMETRIC FATIGUING EXERCISE AND THEIR IMPLICATIONS FOR REHABILITATION FOLLOWING KNEE SURGERY

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GLOSSARY OF TERMS

ACL	Anterior cruciate ligament
ANOVA	Analysis of variance
ATFD	Anterior tibio-femoral displacement
BPTB	Bone-patella tendon-bone
BABE	Bug and Bag Effort
CAC	Cardiovascular/anaerobic/catastrophe
CALER	Cart and Load Effort Rating
CGM	Central Governor Model
CK	Creatine kinase
CON	Control
CR-10	Category-ratio scale of perceived exertion
CTD	Completed task duration
EIMD	Exercise-induced muscle damage
EMD	Electromechanical delay
EMD_{VL}	Electromechanical delay (m. vastus lateralis)
EMD_{VM}	Electromechanical delay (m. vastus medialis)
EMG	Electromyography
ETL	Estimation of time limit
H	Hamstrings
HOP	Single leg hop tests
HR	Heart rate

ICC	Intraclass correlation coefficient
IIF	Intermittent isometric fatigue task
INJ	Injured limb
IKDC	International Knee Documentation Committee
KE	Knee extensors
KF	Knee flexors
kHz	Kilohertz
KOOS	Knee Injury and Osteoarthritis Outcome Score
LSI	Limb symmetry index
MVMA	Maximum voluntary muscle activation
NON	Non-injured limb
OMNI	Title of a commonly used pictorial perceived exertion scale
PASW	Predictive Analytics SoftWare
PF	Peak force
PP	Performance Profile
PTD	Perceived percentage of completed task duration
P_TF_E	Evoked peak twitch force
Q	Quadriceps
RFD	Rate of force development
RPE	Rating of perceived exertion
SD	Standard deviation
SPSS	Statistical Package for the Social Sciences
TD	Task duration

TEA	Task, Effort and Awareness scale
UTT	Unknown time trial
V%	Coefficient of variation
VO_{2max}	Maximum oxygen consumption
VO_2	Oxygen consumption
VT	Ventilatory threshold

ABSTRACT

It has been theorised that self-perception is integral to the regulation of exercise and production of an optimal performance. This concept has not been examined in an anterior cruciate ligament (ACL) reconstructed population where the consequences of injury and surgery may provide a substantive perturbation to perceptual capabilities. Ratings of perceived exertion (RPE) have previously been shown to enable prediction of exercise task duration (TD) during running and cycling activities in healthy individuals, but this has yet to be explored in intermittent and isolated muscle exercise that is typically utilised during resistance training and ACL rehabilitation. Accordingly, this thesis investigated: i) the relationship between self-perceived knee function and objective measures of musculoskeletal performance at a range of time-points across the ACL-rehabilitation period; ii) the relationship between two paradigms of self-perception (RPE; perceived TD) and TD in healthy individuals during an intermittent isometric fatigue task (IIF) under various conditions of increasing exercise stress.

Self-perceived knee function measured via subjective rating scales was only moderately correlated with objective performance towards the latter stages of the rehabilitation period, highlighting a disparity between perceived and actual capabilities during the early to intermediate stages of recovery (pre-surgery to 24 weeks). In contrast to previous research in running and cycling exercise, the investigation of self-perception and TD during an IIF revealed evidence of both linear and curvilinear trends in perceptual response. Linear trends were observed at exercise intensities of 60% to 80% of baseline volitional peak force, whilst curvilinear patterns of response were apparent at intensities of 60% peak force, and under conditions of exercise-induce muscle damage. Evidence of a negatively accelerating curvilinear response may reflect an underestimation of performance, and questions the utility of self-perception to

predict TD in isolated muscle exercise. These combined findings highlight a need for further research before confirming the efficacy of self-perception with regard to regulating exercise during rehabilitative-type activities.

Chapter 1: Introduction

CHAPTER 1: INTRODUCTION

1.1. SELF-PERCEPTION AND EXERCISE REGULATION

The regulation of work-rate and energy expenditure in sport and exercise has previously been described as a pacing strategy (Abbiss and Laursen, 2008). It has been theorised that a performer's rating of perceived exertion (RPE) is integral to this process (St Clair Gibson et al., 2006). In this context, RPE would result from the interpretation of multiple sensory cues and is subsequently matched against a 'template RPE' that represents the performer's expectations of the exercise bout (Tucker, 2009). This template is based on previous experience of the exercise mode and the associated psychological and physiological afferent inputs (Tucker, 2009). To provide support to this theory, RPE has previously been observed to increase linearly in relation to task duration (TD) during running and cycling tasks (Horstman et al., 1979; Noakes, 2004; Eston et al., 2007; Crewe et al., 2008). In these exercise modes, RPE may have the capability to act as a predictor of TD (Horstman et al., 1979; Eston et al., 2007), and enable the adjustment of work-rate in order to preserve homeostasis whilst optimising exercise performance (Ulmer, 1996). In addition, Swart et al. (2009) observed that an increased linearity of RPE responses was associated with a concomitant increase in power output during cycling time trials, suggesting the adoption of a more effective pacing strategy.

Given the important role of prior experience in the generation of RPE (Noble and Robertson, 1996; Tucker, 2009), a novel and unaccustomed exercise task would result in a limited 'template RPE'. Consequently, inaccurate judgments regarding perceived workload during a given exercise bout may result in the subconscious selection of an inappropriate 'template RPE' against which to compare the perceived demands of the task. This may therefore have associated implications for the relationship between RPE and TD. If this relationship deviates from linearity, then the use of RPE in a predictive capacity would provide an inaccurate estimation of TD (as illustrated in Figure 1.1). A worst case-scenario of inaccurate RPE and workload production could predispose an overestimation of capabilities that might expose performers to fatigue-related impairments in neuromuscular performance, such as decreased strength (Zebis et al., 2011), speed of force generating capabilities, delayed muscle response times (Minshull et al., 2007), and sub-optimal movement skill execution (McLean and Samorezov, 2009). Conversely, an underestimation of capabilities might lead to premature cessation of the exercise bout resulting in a sub-optimal level of performance. Whilst the majority of previous research has focused on cycling and running activities, the relationship between RPE and TD has yet to be explored in novel and intermittent exercise tasks. Activities of this nature may have application within a rehabilitation environment where patients are progressively re-introduced to dynamic exercise following surgery (Grodski and Marks, 2008; van Grinsven et al., 2010), or a team sport environment where performers are exposed to regular variations in training stimuli to optimise progression (Gamble, 2006).

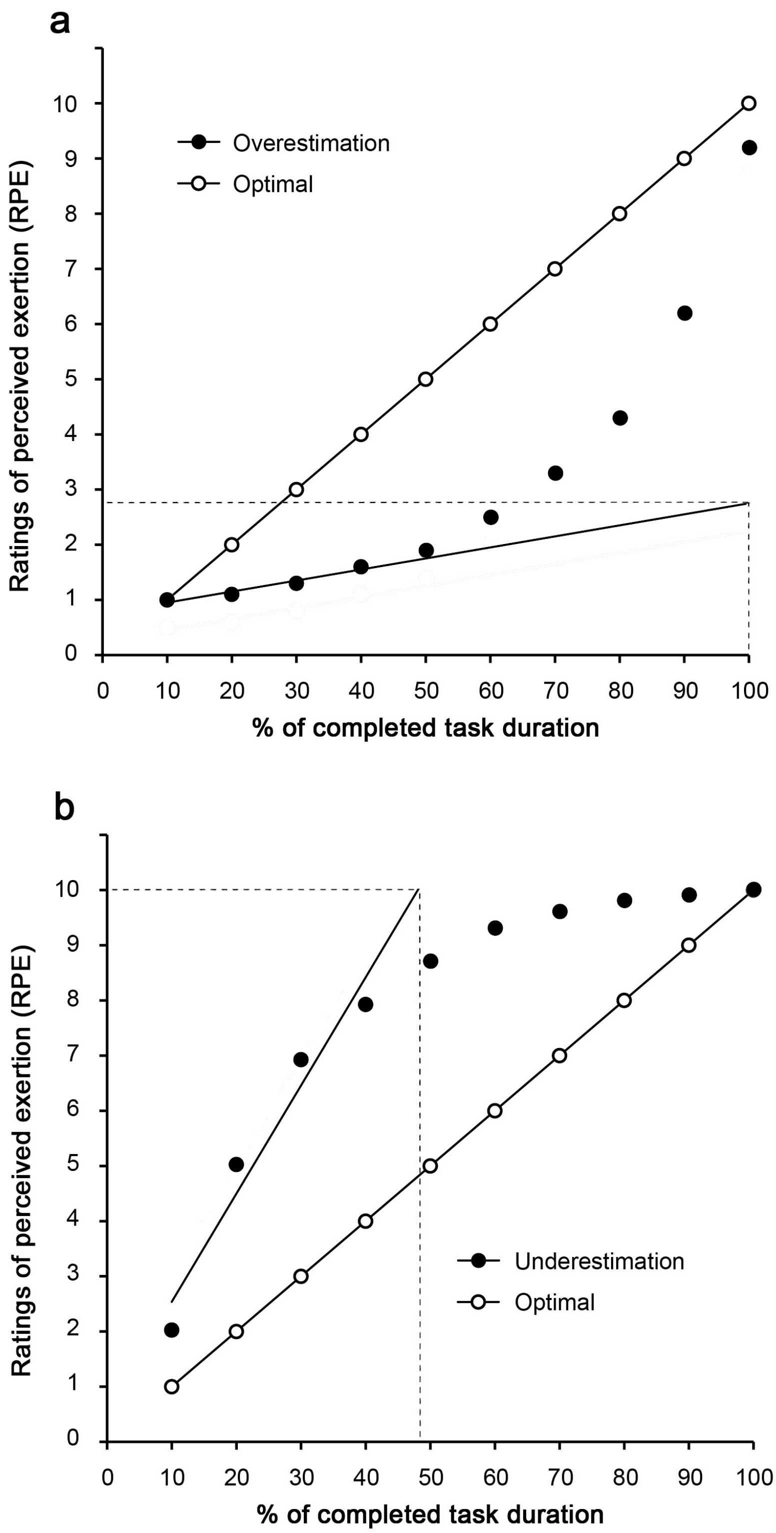

Figure 1.1 a) Theoretical overestimation of TD; b) Theoretical underestimation of TD. The dashed lines highlight the disparity between RPE and TD, based on a prediction from the RPE responses obtained during the early stages of the exercise task.

1.2. SELF-PERCEIVED FUNCTION DURING REHABILITATIVE EXERCISE

Injury to the anterior cruciate ligament (ACL) is a serious and potentially career-threatening injury for many athletes, with up to 250,000 ACL injuries estimated to occur annually (Griffin et al., 2006). Injury to the ACL is common in multi-sprint sports, such as basketball, soccer and American Football (Magnussen et al., 2009), whereby deceleration during landing or cutting movements places the knee under severe translational and rotational stress (Griffin et al., 2006). With most cases of ACL rupture requiring reconstructive surgery to restore knee function (Hurd et al., 2008), the consequences of injury include substantial costs (surgery and associated rehabilitation estimated at over $17,000; Paxton et al., 2010) and a lengthy recovery period (estimated at 6-9 months; Beynnon et al., 2005). Reconstructive surgery creates an inevitable disruption to the knee joint, due to the harvesting of donor tissue from the patient's patella tendon or semitendinosus tendon (Wright et al., 2010). Post-operative rehabilitation requires patients to redevelop range-of-motion, strength and conditioning of the surrounding musculature, and optimal movement patterns in order to restore knee function (Grodski and Marks, 2008; van Grinsven et al., 2010), Throughout this rehabilitation period, most patients will have limited access to specialist supervision (Coppola and Collins, 2009). This places added importance on accurate self-perception of exertion, as patients seek to optimally pace and produce work during their recovery without jeopardising the integrity of the replacement graft (Marumo et al., 2005). An ACL-reconstructed population also faces the added challenge of coping with a considerable perturbation to the knee joint as a consequence of the surgical procedure. This disturbance includes weakening of the donor tendon and associated musculature (Yasuda et al., 1992; Forster and Forster, 2005) and neuromuscular inhibition resulting from pain and swelling (Hopkins and Ingersoll, 2000; Rice and McNair, 2010). These disruptions could potentially impact upon the efficacy of self-perceived capabilities. Inaccurate self-perception of knee function may have associated implications for patients' ability to self-regulate exercise as they progress to a return to full activity. If individuals cannot correctly perceive their capabilities during exercise and rehabilitation tasks and modify their work-rate accordingly, then this may ultimately increase the risk of re-injury to the involved limb. Indeed, a fear of re-injury and lack of confidence in the reconstructed knee have been attributed as possible explanations as to why as many of 67% of patients have not returned to competitive sport as long as 12 months post-surgery (Webster et al., 2008; Ardern et al., 2011b). This lack of self-efficacy may lead to patients applying a cautious strategy to effort production during their rehabilitation, resulting in sub-optimal performance during exercise sessions. Failure to achieve the required goals of a given phase of rehabilitation will prevent the patient from advancing onto the subsequent stage (van Grinsven et al., 2010), thus delaying their progress and extending the recovery period. Implications of this eventuality are increased physiotherapy costs and an extended period of absence from competitive sport. This highlights the need for accurate self-perceived knee-function to provide an accurate reflection of objective capabilities. In addition, exploring the nature of self-perceived knee function during ACL rehabilitation may help to identify any periods during the recovery process where there is a large disparity between self-perceived and objective measures of performance. This could then provide the basis for further investigation into patients' pacing and self-regulation during these critical stages of rehabilitation and, therefore, optimise the rehabilitation process.

1.3. SELF-PERCEPTION DURING INTERMITTENT ISOMETRIC EXERCISE

Whilst the linear relationship between RPE and TD has previously been established in running and cycling tasks, it is yet to be investigated in resistance training or static and isolated muscle work that might generate different sensations of pain and fatigue and provide different perceptual cues (Noble and Robertson, 1996). Such activities form an important component of post-surgical rehabilitation programmes to reduce risk of re-injury and optimise progress (Grodski and Marks, 2008; van Grinsven et al., 2010). It is, therefore, of potential benefit to explore the relationship between self-perception and TD in a mode of activity that could be incorporated into many types of exercise programmes and, in particular, translate to a rehabilitative setting.

A range of perceptual scales have previously been utilised in investigations that have explored the concept of pacing and exercise regulation. These include the Borg 15-point RPE scale (Noakes, 2004; Eston et al., 2007; Crewe et al., 2008; Davies et al., 2009), a category-ratio 0-10 RPE scale (Albertus et al., 2005; Joseph et al., 2008; Swart et al., 2009), and an estimated time limit (ETL) scale (Garcin et al., 1999; Garcin et al., 2004). It is necessary to explore the most appropriate scales that could be applied to intermittent isolated muscle exercise, and to establish the efficacy and reliability of these scales. It is also of value to conduct exploratory investigations of this topic in an asymptomatic population, in order to establish typical perceptual responses that can then provide the basis from which to make future comparisons.

Given the potential importance of an accurate 'template RPE' in exercise regulation and pacing (Tucker, 2009), it is important for performers to detect changes in workload in order to make accurate judgements concerning the demands of the exercise bout. Variations in resistance training intensity of 10% have been shown to provoke significant changes in power output (Thomas et al., 2007) and in the number of repetitions performed (Shimano et al., 2006). For example, a performer undertaking a resistance training programme who is unable to detect a 10% increase in intensity may find themselves unexpectedly struggling to complete the desired number of repetitions of a given exercise. The withholding of precise exercise intensity from participants may therefore prompt a variation in RPE that results from a mismatch between the initially anticipated and actual workloads (Baden et al., 2005). This in turn may cause an inappropriate 'template RPE' to be selected, resulting in a misjudgement of task demands, consequently reducing the effectiveness of the pacing strategy. If participants are unable to detect subtle changes in exercise intensity, then this may have implications for their judgement of how long they can perform a given task, and possibly for their ability to select appropriate workloads as they undertake novel exercise during unsupervised training sessions.

A further challenge for the precise self-perception of exercise stress could involve increasing exercise stress and activities provoking exercise-induced muscle damage (EIMD). This increase in exercise stress potentially reflects that experienced by ACL patients as they are re-introduced to dynamic exercise during rehabilitation. Typically resulting from a bout of unaccustomed exercise (McHugh et al., 1999), EIMD is characterised by soreness in the involved musculature (Proske and Morgan, 2001), and is accompanied by substantive reductions in neuromuscular performance (Minshull et al., 2012) and reduced proprioceptive capabilities (Torres et al., 2010). The sensations of localised pain in the involved musculature, coupled with the impairments to performance capability, could impact upon a performer's RPE and the associated relationship with TD.

1.4. RESEARCH AIMS

In order to examine the issues described above, two main strands of investigation were designed and conducted concurrently. The first strand explores relationships between self-perceived measures of knee function and objective indices of musculoskeletal performance in an ACL-reconstructed population during key stages of the post-operative rehabilitation process. This involves assessing ACL-reconstructed patients at five separate time points, scheduled at pre-surgery, and at 6 weeks, 12 weeks, 24 weeks and at an anticipated completion of rehabilitation at 48 weeks post-surgery (study 1, detailed in Chapter 3). Analysis of these findings aims to identify the stages of the ACL rehabilitation process where there is the greatest disparity between the patients' perceptual measures and their objective measures of knee function. The resulting findings can then form the basis for potential future investigations into the relationship between self-perception responses and TD during rehabilitation-type activities.

The second strand of research focuses on investigating the patterns of perceptual response in relation to TD during a novel intermittent isometric fatigue task (IIF) that reflects the types of static isolated muscle exercise that are incorporated within a typical ACL rehabilitation protocol (van Grinsven et al., 2010). In order to achieve this, the reliability and reproducibility of two perceptual scales first need to be established (study 2, detailed in Chapter 4). These two scales each represent a separate paradigm of effort perception: i) measurement of perceived; ii) measurement of perceived percentage of completed TD. Ascertaining a level of measurement precision for these perceptual scales in an asymptomatic population is necessary to provide a basis from which judgements can be made regarding experimental outcomes in subsequent studies. These subsequent studies explore the capability of the perceptual scales to relate to TD, in order to establish their validity and potential utility in regulating performance during intermittent and static muscle activities. Firstly, the relationship between measures of self-perception (perceived exertion; perceived task duration) and TD is explored during an IIF in an asymptomatic population (study 3, detailed in Chapter 5). Establishing the nature of this relationship is important in order to determine the efficacy of self-perception to act as an accurate predictor of TD, and consequently have the potential to regulate work-rate. In addition, the capability of the two assessment paradigms to reflect a 10% change in work intensity is also investigated. In accordance with the theory of exercise regulation outlined by Tucker (2009), an inability to accurately perceive variations in intensity during the performance of isolated muscle exercise tasks might provoke the selection of an inappropriate 'template RPE' against which to compare the demands of the task, and possibly lead to an inaccurate estimation of capabilities based on the assigned training load. In real terms, this could either result in the performer unexpectedly struggling to complete a bout of exercise, or conversely being able to continue for far longer than anticipated. The inconclusive findings from study 3 necessitated further investigation, as it transpired that a greater differential between IIF work intensities was required in order to help establish the responsiveness of the perceived exertion scale. As such, the subsequent study aimed to evaluate the capability of the two perceptual assessment paradigms (perceived exertion; perceived task duration) to reflect a 20% differential in work intensity (study 4, detailed in Chapter 6).

A final study examines the effects of EIMD upon the relationship between TD and the two perceptual assessment paradigms (perceived exertion; perceived task duration) (study 5, detailed in Chapter 7). As a consequence of this disturbance, sensory cues may be influenced by the presence of EIMD in the involved musculature, and thus alter the nature of the relationship between self-perception and TD. Moreover, this perturbation to neuromuscular function mirrors the introduction of unaccustomed exercise during an ACL rehabilitation programme, thus providing an ecologically valid method of disrupting the neuromuscular system. Investigation into the impact of EIMD upon the relationship between self-perception and TD may, therefore, have considerable relevance to patient populations.

Ultimately, the intention for the direction of this research was to eventually combine the two strands of investigation, by exploring the utility of the two perceptual assessment paradigms during an IIF in an ACL-reconstructed population. This would have been investigated during the stages of rehabilitation that displayed the greatest disparity between the patients' perceptual measures and their objective measures of knee function, as dictated by the findings from the initial empirical study.

Chapter 2: Literature Review

CHAPTER 2: LITERATURE REVIEW

2.1. PACING IN EXERCISE

In sport and exercise, an effective performance requires the individual to complete a given task at an optimal work-rate with optimal energy consumption (Ulmer, 1996). The term 'pacing' has been used to encapsulate how a performer distributes work and energy expenditure with regard to producing an optimal performance (Abbiss and Laursen, 2008). A performer pacing a given task too quickly would be unable to finish because of the early onset of fatigue. However, pacing too slowly would result in a sub-optimal performance. It is hypothesised that pacing strategies enable athletes to regulate their work rate to enable an optimal performance whilst preventing potentially harmful physiological changes, such as dangerously reduced muscle glycogen levels (Tucker, 2009). In addition to a competitive sporting environment, this principle can also be applied to an exercise and training context, where a sub-optimal performance may produce a lack of desired results (Glass and Stanton, 2004) and consequently have a negative impact upon long-term adherence to a training programme (Focht, 2007). Furthermore, continued sub-optimal performance during injury rehabilitation may limit the effectiveness of the recovery process, which in turn would result in increased costs and a delayed return to sport (van Grinsven et al., 2010). For example, a return to full activity following anterior cruciate ligament (ACL) reconstruction is forecast at 6-9 months (Beynnon et al., 2005), but figures indicate that a substantial proportion of patients (~67%) are still to return to full activity by12 months post-surgery (Ardern et al., 2011b).

2.1.1. Pacing Strategies

Pacing typically refers to self-paced exercise, requiring performers to make judgments regarding the adjustment of work-rate in order to achieve an optimal performance and preserve homeostasis (Tucker and Noakes, 2009). However, this concept can also be applied to exercise at a fixed pace or fixed intensity, whereby the performer is required to adjust their work-rate in order to maintain pace, or ultimately decide to terminate the exercise bout (Tucker, 2009). Pacing strategies are commonly utilised when undertaking activities such as swimming, rowing, running and cycling that are performed over a known distance and completed as quickly as possible in competition with an opponent or against the clock (Abbiss and Laursen, 2008; Tucker and Noakes, 2009). Although there are potentially infinite variations of pacing strategies (St Clair Gibson et al., 2006), the selected strategy will depend on the type of activity performed (St Clair Gibson et al., 2006; Abbiss and Laursen, 2008; Tucker and Noakes, 2009). For example, short duration activities (typically <4 minutes; Tucker and Noakes, 2009) are characterised by a 'positive' or 'all-out' pacing strategy, characterised by a fast start with a progressively gradual reduction in power output (Abbiss and Laursen, 2008). This can be seen in sprint cycling and running, where the highest speeds are achieved early in the event (Ferro et al., 2001; Ansley et al., 2004). In contrast, longer duration activities (>4 minutes; Tucker and Noakes, 2009) commonly exhibit a 'negative' pacing strategy whereby there is a significant increase in speed towards the end of the event (Abbiss and Laursen, 2008) frequently referred to as an 'end-spurt' (Marino et al., 2004; Tucker and Noakes, 2009). In addition to these repetitive activities involving reciprocal patterns of muscle activation, pacing strategies can also be applied to more complex and intermittent modes of sport and exercise. Multi-sprint sports, which are characterised by intermittent periods of high-intensity exercise, involve unpredictable demands that necessitate a different pacing approach to cycling or running against the clock. For these types of activity, a hypothetical multi-level pacing model has been proposed (Edwards and Noakes, 2009) involving an overall pacing plan for the entire match (macro-pacing), a pacing plan for each half (mesopacing), and a pacing plan to adapt their overall match pace to the impact of acute bouts of activity during the game (micro-pacing). To the author's knowledge, pacing has yet to be explored in intermittent tasks that may have application to resistance training or rehabilitation activities. Whilst not directly referred to as 'pacing', the importance of judging the maintenance of power output during resistance exercise has previously been emphasised (Naclerio et al., 2011).

2.1.2. Anticipation of fatigue

It is of value for a pacing strategy to be formulated in anticipation of increasing levels of fatigue and to help self-regulate work-rate accordingly. Fatigue has been described as "an acute impairment of performance that includes both an increase perceived effort necessary to exert a desired force and an eventual inability to provide this force" (Enoka and Stuart, 1992, p. 1631). In broader terms, the concept of fatigue reflects an exercise-induced impairment of performance (Knicker et al., 2011), manifested by decreased strength levels (Zebis et al., 2011), a reduction in muscle response times and speed of force generating capabilities (Minshull et al., 2007), and sub-optimal movement skill execution (McLean and Samorezov, 2009). In addition, a greater incidence of injuries has been reported in the latter stages of match-play and training sessions in multi-sprint sports such as rugby and soccer (Gabbett, 2000; Gabbett, 2003; Price et al., 2004) that could also be fatigue-related (Gleeson et al., 1998). The combination of these factors may provide a potential link between fatigue and increased risk of injury. An athlete's capability to implement an effective pacing strategy may be important in minimising injury risk in conjunction with optimising performance. In order to gain a better understanding of the concept of pacing, it is, therefore, necessary to explore the potential mechanisms that govern the perception of exercise stress and regulation of exercise performance.

2.2. REGULATION OF EXERCISE PERFORMANCE

There is some disagreement concerning the underlying mechanisms governing the regulation of exercise performance, with recent debate focusing on the role of the brain during physical activity (Weir et al., 2006; Marcora, 2008; Tucker and Noakes, 2009; Shephard, 2009; Marino, 2010; Noakes, 2011). The traditional catastrophe model of exercise regulation – recently termed the cardiovascular/anaerobic/catastrophe (CAC) model (Weir et al., 2006), stipulates that fatigue and the termination of exercise is due to the accumulation of metabolites or energy substrate depletion and the associated loss of homeostasis (Edwards, 1983; Weir et al., 2006; Shephard, 2009). This fatigue may result from changes to the muscle cells (peripheral fatigue) and/or reduced activity from the central nervous system (central fatigue) (Westerblad and Allen, 2002). Peripheral fatigue may involve depletion of intramuscular energy stores in addition to the accumulation of anaerobic metabolites such as potassium (Bangsbo et al., 1996) and inorganic phosphate (Nordlund et al., 2004). Central fatigue, via reflex inhibition of spinal motorneurons or inhibition of volitional supraspinal commands, may be induced as a consequence of hydrogen ion accumulation and associated stimulation of nociceptors resulting in perceived discomfort in the involved muscles (Stackhouse et al., 2001; Westerblad and Allen, 2002). More recently, it has been argued that fatigue is actually a sensation arising from the conscious perception of these subconscious physiological processes, rather than simply a physical event (Noakes et al., 2005; Noakes 2011). This differing viewpoint challenges existing paradigms concerning fatigue and exercise regulation, and forms the basis for the argument behind the governing of pacing strategies.

In more recent years, the Central Governor Model (CGM) has gained favour as an alternate theory to describe the regulation of exercise, and suggests the brain interprets afferent feedback arising from exercise and applies this information to make strategic decisions regarding the adjustment of work-rate and ultimately to terminate exercise before homeostasis is disrupted (Lambert et al., 2005; Noakes et al., 2005; Noakes 2011). Advocates of the CGM hypothesise that a pace is selected at the start of an exercise task, resulting from the interpretation of sensory feedback derived from a range of sensory receptors and matched against an anticipated outcome or 'end-point' (Noakes and St Clair Gibson, 2004; St Clair Gibson et al., 2006). An integral part of this process involves the interpretation of numerous physiological and psychological cues to enable the generation of a subjective rating of perceived exertion (RPE) (Tucker and Noakes, 2009). This RPE[1] is subsequently compared against a 'template RPE' that is based on prior experience of the mode of exercise (Tucker, 2009). The selected pace is then constantly re-calculated in an ongoing process that has been previously defined as teleoanticipation (Ulmer, 1996; St Clair Gibson et al., 2006) and is illustrated in Figure 2.1.

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[1] The term RPE has evolved in recent years, from originally being attributed as the title of a scale of measurement (Noble and Robertson 1996; Borg, 1998; Robertson, 2001) to more recently being used as a generic term to describe the psychological construct of perceived exertion (Tucker, 2009; Eston, 2012).

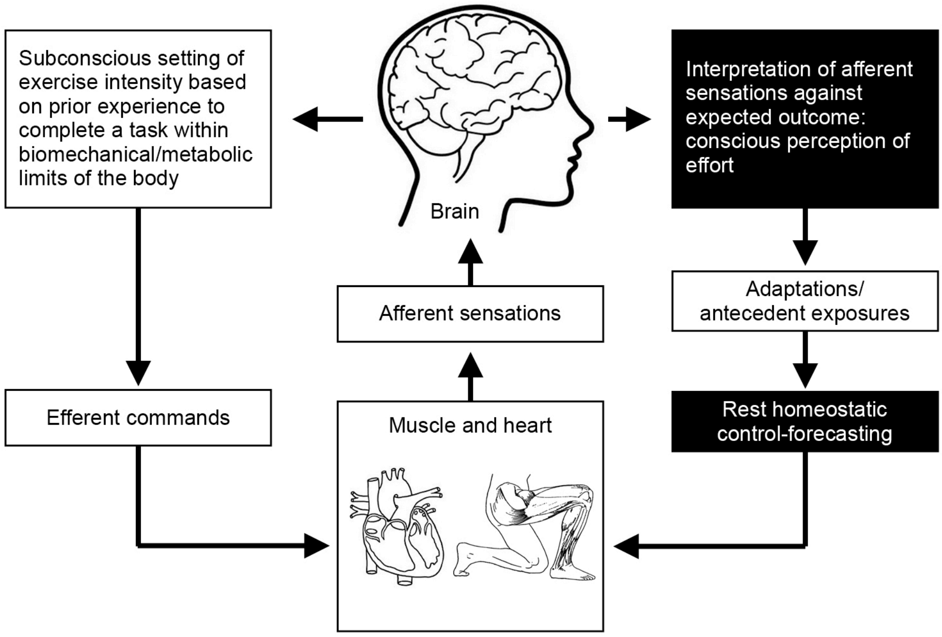

Figure 2.1. The teleoanticipatory process of exercise regulation (adapted from Lambert et al., 2005)

An alternative psychological-motivational model of exercise regulation has been proposed that disassociates RPE from the sensory feedback resulting from exercise (Marcora, 2008). This model theorises that RPE is created as a consequence of efferent commands to the involved muscles (Marcora, 2009). During prolonged sub-maximal exercise at a constant work-load, an increase in fatigue requires a compensatory increase in central motor commands to the involved musculature and the respiratory system (Marcora, 2008). The resulting corollary discharges are forwarded to the sensory cortex where a conscious RPE is generated (Marcora, 2008). This theory is based upon previous evidence that demonstrates that RPE is maintained or increased in the absence of afferent feedback from the involved muscles (due to epidural anaesthesia; Smith et al., 2003), the heart (due to beta-adrenergic blockade; Myers et al., 1987), and the lungs (due to anaesthesia of the airway; Winning et al., 1988).

2.2.1. Implications of popular models for pacing

The different theoretical models outlined above have different implications when applied to the concept of pacing. It has been suggested that an 'all-out' approach to an event such as the 100m sprint is evidence of a rapid implementation of a pacing strategy, thus supporting the CGM theory (Noakes et al., 2005). Conversely, Weir et al. (2006) argue that patterns of work characterised by initial acceleration, maintenance of maximum velocity, and an eventual decrease in velocity towards the end of a short duration event, such as that described by Noakes et al. for the 100m sprint actually provides evidence of a lack of pacing strategy. With regard to longer duration activities, Noakes, (2011) postulates that exercise regulated solely by the CAC model would not permit an increase in work-rate towards the end of a longer duration event (as seen by the 'end-spurt' phenomenon) and indeed would only enable one type of pacing for exercise of all modes and duration. In accordance with the CGM model, the changes in work-rate associated with a pacing strategy would therefore occur as part of an anticipatory regulatory strategy to prevent damage to bodily structures (Noakes et al., 2005). A counter-argument from Shephard (2009) acknowledges that the brain is involved in selecting a pace at a level where minimal lactate accumulates in the working muscles, thus enabling an end-spurt to fully exploit the athlete's anaerobic capacity. However, Shephard theorises that whilst psychological factors including motivation and arousal can sustain or enhance an individual's exercise performance, the primary limiting factors are physiological, such as maximal anaerobic power and capacity, maximal aerobic power and capacity, and the availability of energy substrates, minerals and water. A key argument used in support of the CGM involves the role of sensory feedback in enabling the brain to select an appropriate pace and preserve homeostasis (Noakes, 2004). Reports of a linear relationship between RPE and exercise duration have prompted the theory that RPE is informed by a subconscious glycogen-based signal during exercise (Noakes, 2004). It is hypothesised that exercise limited solely by energy substrate depletion would be characterised by a rapid increase in RPE towards the end of the exercise bout when glycogen stores are critically low, as opposed to the observed gradual increase in RPE with a concomitant reduction of glycogen (Tucker, 2009). This finding has been provided as evidence of an adjusted work-rate resulting from the brain's conscious interpretation of afferent feedback (Noakes, 2004).

2.2.2. The role of the brain in exercise regulation

The different theories of exercise regulation have prompted debate regarding the precise role of the brain in the process of exercise regulation (Spurway et al., 2012; Amann and Secher, 2010; Marcora, 2009). Considerable focus has been placed upon attempting to determine the limiting factor(s) in exercise performance, with evidence both for and against the concept of a central governor. For example, it is suggested that exercise performance in the heat is limited by the body reaching a critical internal temperature that threatens homeostasis (Gonzalez-Alonso et al., 1999). In self-paced exercise in the heat, a reduction of power output has been found to occur before the body reaches this critical internal temperature, suggesting that increases in RPE may prompt a centrally-governed regulation of performance (Nybo and Nielsen, 2001). Moreover, a study by Morrison et al. (2004) that involved a series of maximal isometric contractions performed at progressively increasing core temperatures from 37.5°C to 39.5°C reported a corresponding gradual decrease in muscle force. It has been proposed that to be consistent with the CAC model, force would instead have remained constant until the core temperature reached critical levels (Tucker and Noakes, 2009). However, in extreme cases, a failure of homeostasis as a result of a critical increase in core temperature can manifest itself as risk of death from heat stroke in sports such as American Football (Mueller, 2003) and endurance running (Roberts, 2007). In these instances, death from hyperthermia would represent an extreme example of a failure of the CGM to limit exercise performance.

Additional evidence has been presented in support of the respective models of exercise regulation. For instance, an investigation into repeated sprint activity by Gaitanos et al. (1993) revealed a curvilinear rate of decline in performance before stabilising after approximately 50% of the trials. It is suggested that if metabolite accumulation or substrate depletion were the sole limiting factor behind the decline in performance, then a continued linear rate of decline would have been evident until the participants reached complete exhaustion (St Clair Gibson et al., 2001). However, this theory does not consider the important role of hydrogen ion buffering capacity in repeated sprint ability (Bishop et al., 2004) that may provide some explanation for the plateau effect observed after 50% of the trials. Other supporting evidence for the CGM has been provided with the observation that individuals have been found to terminate exhaustive exercise at altitude with lower rates of cardiac output and lactate accumulation when compared to values obtained at sea level (Sutton et al., 1988). In contrast, it has been highlighted that reduced spinal reflex activity, as measured during perturbation to the ankle joint, is evident following fatiguing exercise (Jackson et al., 2009). Given that spinal reflexes are independent of supraspinal control and are not addressed by the CGM, it is, therefore, theorised that the CGM theory cannot fully explain all aspects of fatigue and exercise regulation (Weir et al., 2006).

Addressing the issue of exercise regulation is necessary to appreciate the underpinning theory behind the concept of pacing. It has been argued that each of the different regulatory models cannot fully explain the concept of fatigue in all exercise scenarios, and therefore attempting to find one theory that encapsulates all possible explanations is a somewhat futile endeavour (Weir et al., 2006). Despite the various arguments, there appears to be a certain level of agreement that the brain does fulfil some role in regulating exercise, both in terms of perception of physiological status and prior experience of exercise stresses (Lambert et al., 2005; Weir et al., 2006; Shephard, 2009; Noakes 2011; Spurway et al., 2012). In practical terms, the issue of primary concern for this thesis centres on whether self-perception of exertion and exercise demands provides an accurate indication of a performer's capabilities, and thus act as a predictor of exhaustion time in a given exercise task. From the arguments outlined above, it is conceivable that an individual's exercise regulation and pacing is based upon two key factors: i) the self-perception of their physiological state at any given moment, based on their conscious interpretation of integrated sensory feedback and/or efferent commands; ii) the judgment of how long they can maintain the current work-rate, based on those perceptions. It is, therefore, worthwhile to identify the various factors that contribute to self-perception of physiological state, and the various perceptual scales that enable measurement of this construct.

2.3. SELF PERCEPTION OF EXERCISE DEMANDS

Perceived exertion is a psychological construct that refers to the interpretation of sensations arising from physical activity (Noble and Robertson, 1996), integrating afferent cues from peripheral muscles and joints, and the cardiovascular, respiratory and central nervous systems (Borg, 1990). A global explanatory model of perceived exertion encompasses a multitude of physiological and psychological factors that contribute to a conscious RPE (Noble and Robertson, 1996). This model proposes that changes in physiological function in response to an exercise stimulus provide an initial perceptual cue. Consequently, any requirement to increase tension in respiratory, skeletal or cardiac muscle would involve a concomitant increase in efferent commands. The resulting corollary discharges are subsequently transmitted to the sensory cortex where they are integrated with afferent feedback arising from the exercise task. This perceptual signal is then matched against the individual's prior experience and psychological characteristics in a perceptual-cognitive reference filter. A perceptual response is then produced that can be differentiated to the respiratory system, the involved limbs, or nonspecific mediators (examples of these are provided in Table 2.1). Alternatively, these signals can be combined to produce an overall perceptual response for the entire body.

Cues arising from changes in physiological function have previously been categorised as central or local (peripheral) factors (Pandolf, 1978; Mihevic, 1981; Watt and Grove, 1993). Central cues encompass cardio-respiratory sensations, whereas local cues relate to feelings of tension in the involved muscles and joints (a more detailed list of these perceptual cues is presented in Table 2.1). In addition, non-specific cues (for example, skin and core temperature, and carbohydrate availability) and psychological cues (such as motivation and personality disposition) may also influence RPE (Noble and Robertson, 1996). Although strong relationships have been found between RPE and factors such as heart rate and blood lactate, correlational evidence does not imply causality (Watt and Grove, 1993; Hampson et al., 2001). Indeed, it has been proposed that RPE cannot be consistently explained by any isolated physiological variable, and that it results from the integration of multiple sensations (Hampson et al., 2001). The mode and intensity of exercise may dictate which of the different mediators provides the dominant contribution to perception in any given situation. For example, minute ventilation and heart rate only become significant predictors of RPE when exercise intensity is greater than 75% VO_{2max} (Noble et al., 1986).

Table 2.1 Evidence relating to the impact of perceptual cues upon RPE

Perceptual cue		Evidence
Central Cues		
Heart rate	*Supporting evidence*	• High correlation between heart rate (HR) and RPE (Skinner et al., 1973; Stamford and Noble, 1974)
	Conflicting evidence	• Pharmacological manipulation of HR does not affect RPE (Ekblom and Goldbarg, 1971; Davies and Sargeant, 1979) • Eccentric exercise associated with higher RPE than concentric exercise at equivalent HR (Pandolf et al., 1978) • Cycling at equivalent power outputs produced lower HR but higher RPE at a lower cadence (40rpm) in comparison to a higher cadence (60 or 80rpm) (Pandolf and Noble, 1973)
Oxygen uptake	*Supporting evidence*	• Patients receiving beta-blockade demonstrate reduced HR but RPE at given percentage of VO_{2max} is not significantly different (Ekblom and Goldbarg, 1971)
	Conflicting evidence	• Eccentric exercise associated with higher RPE than concentric exercise at equivalent VO_2 (Pandolf et al., 1978) • Cycling at equivalent power outputs produced similar VO_2 but higher RPE at a lower cadence (40rpm) in comparison to a higher cadence (60 or 80rpm) (Pandolf and Noble, 1973)
Ventilation and respiratory rate	*Supporting evidence*	• Respiratory rate and RPE found to be higher at slower vs. faster pedalling rates (Robertson et al., 1979)
	Conflicting evidence	• Higher RPE at a lower cadence (40rpm) vs. higher cadence (60rpm), but no change in minute ventilation (Stamford and Noble, 1974)
Local Cues		
Blood lactate level	*Supporting evidence*	• Increase in exercise intensity associated with concomintant increases in lactate and RPE (Gamberale, 1972) • Comparison of treadmill and cycle ergometer exercise reported similar RPE at varying blood lactate levels, despite differences in HR and VO_2 (Hetzler et al., 1991) • RPE values at lactate threshold unchanged after 10-week training programme, despite increases in and VO_2 work-rate (Boutcher et al., 1989)
	Conflicting evidence	• Lactatc responses during cycling at various cadences did not correlate with RPE (Lollgen et al., 1980)
Blood and/or muscle pH	*Supporting evidence*	• Lower RPE values reported in alkalotic vs. control conditions (Robertson et al., 1986)
Strain	*Supporting evidence*	• Significantly higher RPE at lower cycling cadence (40rpm) in comparison to higher cadences (Pandolf and Noble, 1973; Stamford and Noble, 1974) • Eccentric exercise produced higher RPE than concentric exercise at equivalent HR and VO_2 (Pandolf et al., 1978)

Muscle damage	*Supporting evidence*	• RPE values reported to be higher at a lower relative metabolic cost following muscle damaging exercise (Twist and Eston, 2009)
Non-specific Cues		
Temperature	*Supporting evidence*	• Concomitant increases in RPE and skin temperature evident during cycling in hot, neutral and cool conditions (Maw et al., 1993)
Carbohydrate availability	*Supporting evidence*	• Participants ingesting carbohydrate reported lower RPE values during 100-140 mins of cycling in comparison to participants ingesting placebo (Kang et al., 1996)
Catecholamine secretion	*Supporting evidence*	• RPE found to positively correlate with levels of norepinephrine (r = 0.63) and epinephrine (r = 0.54) (Skrinar et al., 1983)
Psychological Cues		
Situational	*Supporting evidence*	• Males found to provide higher RPE responses in the presence of a female experimenter (Boutcher et al., 1988) • Cyclists provided higher RPE responses when riding at 50% VO_{2max} alone in comparison to riding alongside a coactor riding at 25% VO_{2max} (Hardy et al., 1986)
Dispositional	*Supporting evidence*	• Levels of extroversion found to share an inverse relationship with RPE (-0.62 to -0.71) (Morgan, 1973) • Strong positive correlations observed between associative thinking (focusing attention on sensory feedback) and RPE during exercise (Schomer, 1986)

One issue evident within this topic area is a degree of ambiguity associated with the precise definition of RPE. Traditionally, perceived exertion has been defined as including “feelings of effort, strain, discomfort, and/or fatigue experienced during both aerobic and resistance exercise” (Robertson, 2001, p. 191). A more recent contrasting theory of perceived exertion is provided by Marcora (2009), who postulates that RPE is generated by efferent commands and is independent of sensory feedback. Termed the ‘Corollary Discharge Model’, this has been based on observations of RPE measures being maintained or elevated in the absence of afferent cues, as described previously (Myers et al., 1987; Winning et al., 1988; Smith et al., 2003). However, this theory is in its relative infancy and a need for further research has been acknowledged (Marcora, 2009). In some cases, the terms ‘exertion’ and ‘effort’ appear to be used interchangeably (Marcora, 2009; Amann and Secher, 2010; Smirmaul Bde, 2012).

Noble and Robertson (1996) provide a distinction between the terms ‘perceived exertion’ and ‘perceived effort’. They clarify their interpretation of the term ‘exertion’ as the perceived discomfort or strain experienced when performing a given exercise task, as opposed to exertion being solely a reflection of effort exerted during physical activity. Abbiss and Pfeiffer (2010) suggest that whilst perceived exertion may reflect sensations of discomfort, perceived effort may be influenced by previous experience and self-efficacy in performing an exercise task. They propose that an ‘end-spurt’ in the latter stages of a race would see an increase in perceived effort despite a pre-existing high level of perceived exertion. Conversely, some authors (Marcora, 2009; Smirmaul Bde, 2012; Swart et al., 2012) have made a distinction between the sensation of exertion and the associated feelings of pain and discomfort. In this example, an athlete approaching the end of an exhaustive task would simultaneously experience high levels of exertion and discomfort. Immediately upon completion of the task, the level of exertion would be minimal whereas the sensation of discomfort would still be elevated. From reviewing this recent literature, a lack of consistency in terminology and clear definition of RPE is apparent. For the purpose of this thesis, use of the term RPE will encompass sensations of effort and discomfort arising from exercise, although certain distinctions will be made where appropriate.

2.4. MEASUREMENT OF SELF-PERCEIVED EXERCISE CAPABILITIES

A number of scales have been developed to enable measurement of RPE. These typically require the performer to select a numerical value that corresponds to the sensations of effort, discomfort, and possibly fatigue that they are experiencing at that moment (Robertson, 2001). However, more recent developments have involved the design of scales that request the participant to consciously estimate the time remaining to exhaustion (Garcin et al., 1999) and that to differentiate between exertion and effort (Swart et al., 2012).

2.4.1. 15-point Borg Scale

The most commonly used measure of RPE is the 15-point scale developed by Borg (1982). This scale was designed to grow linearly in relation to heart rate and exercise intensity (Borg, 1990), with the starting value of 6 corresponding to an estimated adult resting heart rate of 60 (Borg, 1998). Numerical values of 6-20 are accompanied by various verbal descriptors ranging from 'no exertion at all' to 'maximal exertion'. The scale has been used in numerous studies to provide estimates of RPE in a range of exercise modalities. A meta-analysis investigated the validity of relationships between the 15-point Borg scale and six physiological variables identified as mediators of RPE (Chen et al., 2002). Mean validity coefficients were reported for heart rate (0.62), blood lactate (0.57), VO_{2max} (0.64), VO_2 (0.63), ventilation (0.61), and respiration rate (0.72). Given the positive relationship that the 15-point Borg scale enjoys with these physiological variables, it has been utilised extensively in exercise prescription as a method of monitoring exercise intensity (Noble and Robertson, 1996) and also in terms of producing a level of exertion as a guide for the intensity of a training programme (Robertson, 2004). Whilst the scale has also been utilised in resistance exercise (Eston and Evans, 2009; Tiggeman et al., 2010; Row et al., 2012), its deployment in this setting is limited in comparison to endurance-based exercise, such as running or cycling.

2.4.2. Category-Ratio Scale (CR-10)

The original purpose of Borg's category-ratio scale (CR-10) was to provide a measure that represented the positively accelerating, non-linear growth function associated with the combination of perceived exertion and pain (Borg, 1998). As such, this scale is recommended for use in exercise that may produce sensations of exertion and discomfort in a specific muscle group or area of the body (Buckley and Eston, 2007). The numerical 0-10 scale is also accompanied by verbal descriptors, whereby 10 is defined as "extremely strong" and represents the strongest exertion the participant has experienced. A novel feature of this scale in comparison to the 15-point Borg scale is the inclusion of a higher 'maximal' value. Whilst this enables participants to select ratings of 11, 12 or higher, should the combined sensation of exertion, pain and discomfort be greater than experienced previously, this feature could also affect the efficacy of inter-individual comparisons, as differences in prior experience could be reflected in a wide range of 'maximal' responses. Accordingly, deployment of this scale should be restricted to a homogenous sample population, with clear instructions provided during its administration. In order to improve its utility, elements of the CR-10 scale have been adapted in recent years, such as the re-wording of descriptors to help increase understanding for participants (Lloyd et al., 1991; Pincivero et al., 2003a).

2.4.3. Pictorial RPE scales

The utility of the 15-point Borg scale in a child population is reliant on a combination of age, reading ability, prior experience and level of conceptual understanding (Faulkner and Eston, 2008). This has prompted the development of scales with a limited numerical range and more common descriptors, such as the Children's Effort Rating Table (Williams et al., 1994) and the pictorial OMNI scales (Robertson et al., 2000; Utter et al., 2002). More recently, this theme has been expanded with the development of Cart and Load Effort Rating (CALER) and Bug and Bag Effort (BABE) rating scales (Parfitt et al., 2007). With these scales, the inclusion of an accompanying pictorial system provides more meaningful references for children that may increase understanding and aid in the regulation of exercise intensity (Robertson, 2004). An additional benefit of the OMNI scale over the 15-point Borg scale is the simplified numerical rating range of 0 to 10 that increases ease of understanding (Robertson, 2004). Despite being originally designed for children, mode-specific versions of the OMNI scale have been validated for use with both children and adults in various forms of endurance exercise (Robertson et al., 2004; Utter et al., 2004; Robertson et al., 2005b; Mays et al., 2010) and resistance exercise (Robertson et al., 2005a; Lagally and Robertson, 2006; Colado et al., 2010). However, Faulkner and Eston (2008) have queried which aspect of the pictorial scale (the picture, the location of the picture or the magnitude of the number) is afforded the greatest attention by the participant during exercise tasks, thus questioning the need for mode-specific OMNI scales.

2.4.4. Estimated Time Limit Scale

Rather than employ RPE as a predictor of exercise duration, Garcin et al. (1999) focused on whether or not participants could consciously predict exhaustion time. This led to the development of a logarithmic Estimation of Time Limit (ETL) scale. The application of the scale involves participants being asked the question "how long would you be able to perform an exercise at this intensity up to exhaustion?" and then recording their responses on a scale consisting of values between 1 and 20 ranging from "more than 16 hours" (scale point 1) to "2 minutes" (scale point 19). Since its development, utility of the ETL scale has been explored in running (Garcin et al., 2004), cycling (Garcin et al., 2011) and in both self-paced and fixed-paced exercise (Garcin et al., 2008). Support has been provided for the test-retest reliability of the ETL scale through the use of Pearson correlation coefficients (r=0.95) (Garcin et al., 2003). However, this approach of establishing reliability has been criticised as the use of correlation coefficients only provide a measure of association as opposed to an indication of variability (Lamb et al., 1999). Establishing the validity of the ETL has proved more problematic, with findings indicating a lack of capability of the scale to predict exhaustion time (Garcin et al., 2004; Coquart and Garcin, 2007). More recently, evidence to support the validity of the ETL in a prescriptive context has been provided, due to the similarity in work performed during estimation and production tests (Garcin et al., 2012). However, the utility of the ETL scale as a method of prescribing exercise intensity is in contrast to its original intended purpose of providing a prediction exhaustion time in a given exercise task.

2.4.5. Task, Effort and Awareness Scale

More recently, Swart et al. (2012) devised a task, effort and awareness scale (TEA) that attempted to distinguish between the sensations arising from exercise and the awareness of effort required to perform an exercise task. The TEA scale requires participants to rate the psychological effort required to perform an exercise bout at a given intensity. The authors differentiate this from the traditional 15-point Borg RPE scale by instructing participants to provide RPE responses that reflected the physical sensations resulting from the exercise as opposed to the psychological demand of continuing the task. In order to enable direct comparison to the 15-point Borg scale, the TEA scale employs a 15-point system that ranges from -4 to 10. The selection of a rating of -4 indicates a lack of awareness of any mental effort required to continue the exercise task, and therefore an absence of sensations informing the participant to "slow down". In contrast, a 10 equates to a constant awareness of a severe effort required to maintain the current pace that will require the participant to "slow down" (J. Swart, personal communication, June 19, 2012).

The TEA and modified 15-point Borg RPE scales were used concurrently during both a maximal-effort 100km cycling bout and a sub-maximal 100km cycling bout, each containing a series of maximal effort 1km sprints. Whilst the TEA scale responses were close to maximal (10) following each individual sprint, the RPE responses increased progressively with each sprint. This finding may offer evidence that the TEA scale provides a measure of effort that is separate from the physical sensations resulting from exercise, which is measured by RPE. However, this distinction is achieved in part by altering the characteristics of the 15-point Borg RPE scale to isolate afferent sensations from the efferent commands required to generate 'effort'. As such, this creates difficulties in comparing these results with other studies that have utilised the 15-point Borg RPE scale.

2.5. PERCEIVED EXERTION AND EXERCISE REGULATION

Whilst the scales described in Section 2.4 have been used in a variety of settings to monitor RPE, their utility has also extended to a prescriptive context as a method of regulating work-rate (Dunbar et al., 1992; Dishman, 1994; Noble and Robertson, 1996). In these instances, performers undertake an estimation-production procedure, whereby RPE values are assigned to corresponding intensities in a graded exercise task (estimation), and then used to prescribe workloads during subsequent exercise bouts (production) (Faulkner and Eston, 2008). The benefits of this approach to exercise regulation are that no costly physiological monitoring equipment is required, and that the estimation-production production process is relatively simple for performers to learn (Dunbar et al., 1992). Additionally, in instances where an individual has considerable experience of a given exercise mode, a production-only method has also been recommended that directs the performer to train within a designated 'training zone' as dictated by their RPE (Robertson, 2004). The RPE estimation-production paradigm has previously been explored in a variety of exercise modes, including cycle ergometry (Dunbar et al., 1992; Robertson et al., 2002; Hartshorn and Lamb, 2004), treadmill exercise (Dunbar et al., 1992; Green et al., 2002; Kang et al., 2003; Parfitt et al., 2012;

Faulkner et al., 2012), stepping (Yelling et al., 2002), resistance training (Row et al., 2012), and isolated static muscle exercise (Pincivero et al., 2003b). In addition, this method has been recommended for deployment in both clinical (Noble, 1982; Noble and Robertson, 1996) and asymptomatic populations (Buckley and Eston, 2007). Despite the widespread usage of RPE in the prescription and regulation of exercise, its efficacy has been questioned due to a lack of research-based evidence supporting the method's level of reliability (Hartshorn and Lamb, 2004). Indeed, the RPE production paradigm is yet to be recommended by the American College of Sports Medicine as a primary method of prescribing exercise intensity, with their position stand highlighting a need for greater supporting evidence (Garber et al., 2011). Hartshorn and Lamb (2004) observed unfavourable levels of test-retest reliability for the RPE production method across 4 identical effort production cycling trials. The authors reported an unacceptably high coefficient of variation (>10%) that failed to improve with repeated trials. In practical terms, this meant that a power output produced in response to a prescribed RPE level on a given day could vary by ±10% in a subsequent trial. It is plausible, however, that the heterogeneous nature of the sample (male and female participants of differing fitness levels) may have contributed to the level of variability in response. Notwithstanding these concerns, the RPE estimation-production method has been shown to promote gains in cardiovascular fitness. Parfitt et al. (2012) reported significant improvements to VO_{2max}, mean arterial pressure, total cholesterol, and body mass index in a sedentary group following 8 weeks of training at an exercise intensity equivalent to an RPE value of 13.

Although the estimation-production paradigm of regulating work-rate can be utilised during self-paced exercise, the performance of constant-load tasks requires different considerations. These considerations involve the performer having to estimate their RPE at any given point in time, and then making accurate judgements as to how long they can maintain the current work-rate, based on those perceptions. It is, therefore, necessary to explore the existing literature with regard to identifying patterns of perceptual response in relation to exercise duration. This will help to determine the capacity of the various perceptual scales for predicting end-point during exercise tasks, and consequently provide some indication as to the utility of these scales in the regulation of performance during constant-load exercise.

2.6. SELF-PERCEPTION AS A PREDICTOR OF EXERCISE DURATION

Numerous studies have reported patterns of change in RPE in response to exercise duration (examples of these investigations are summarised in Table 2.2). A linear relationship between RPE and exercise duration in both incremental and constant load exercise tasks was first discovered in the 1970s (Morgan and Borg, 1976; Horstman et al., 1979). In practical terms, this would mean that an RPE value selected during the early stages of the exercise bout could be used to predict the duration of the task. This concept is of considerable benefit, as establishing a reliable method of predicting exercise duration would enable performers to optimise performance in anticipation of increasing levels of fatigue, whilst maintaining homeostasis and potentially minimising injury risk. In more recent years, several studies have reported further evidence to support a linear relationship between RPE and exercise duration (Noakes, 2004; Albertus et al., 2005; Eston et al., 2007; Crewe et al., 2008; Faulkner et al., 2008; Joseph et al., 2008; Davies et al., 2009). However, when examining these studies in greater detail it is apparent that a variety of approaches have been adopted to explore the patterns of RPE response. It is beneficial to present some detailed examples of these different methods, in order to provide scope for comparing investigations and evaluating key findings.

Table 2.2 Approaches to the exploration of exercise duration in relation to self-perception measures

Authors	Participants	Familiarisation/ pre-testing session(s)	Exercise protocol	Scale	Key findings
Morgan and Borg (1976)	30 adult males (no description of training background)	No details of familiarisation procedures	Incremental cycling task performed to volitional exhaustion	Borg 15-point RPE scale	Linear increase of RPE as a function of increase in work (R = 0.65).
Horstman et al. (1979)	26 adult males (no description of training background)	Participants familiarised with treadmill walking and running prior to testing	Maximal walking and running trials performed at 80% VO_{2max} to volitional exhaustion	Borg 15-point RPE scale	Early pattern of RPE can be used as a predictor of exhaustion time (linearity observed via descriptive statistics).
Garcin et al. (1999)	51 male athletes (no detail of sporting background)	No details of familiarisation procedures	Incremental cycling task performed to volitional exhaustion	Borg 15-point RPE scale and ETL scale	ETL was linearly related to time up to VT (r = 0.99). Trend analysis revealed a steeper rise in ETL response above VT. ETL recommended in conjuction with RPE to predict VT.
Garcin et al. (2004)	20 endurance-trained males (8 high fitness level; 12 moderate fitness level)	Incremental VO_{2max} test performed on running track	Constant speed running trial to volitional exhaustion (regulated by pacing cyclist)	Borg 15-point RPE scale and ETL scale	No significant differences in RPE or ETL response between groups. Linear extrapolation of RPE and ETL values obtained at minutes 2 and 4 did not predict exhaustion time.

Authors	Participants	Familiarisation/ pre-testing session(s)	Exercise protocol	Scale	Key findings
Noakes, (2004) *{using data from Baldwin et al., 2003}*	7 endurance-trained males	No familiarisation session	2 constant load cycling tasks performed to volitional exhaustion in (i) a glycogen loaded state, and (ii) a glycogen depleted state	Borg 15-point RPE scale	Linear increase of RPE with time (linearity observed via descriptive statistics).
Albertus et al. (2005)	15 competitive endurance-trained male cyclists	Cycle ergometer test to determine peak power output and separate familiarisation of time-trial	4 cycling time-trials with varied deception of distance feedback	CR-10 scale	Deception of distance feedback had no significant effect on RPE. Linear increase of RPE with time (r = 0.96).
Marcora and Bosio (2007)	24 male and 6 female participants with background in distance running	VO2max test	2 running time-trials with participants randomly assigned to a muscle damage or control condition	Borg 15-point RPE scale	Muscle damage had no significant effect on RPE. Linear increase of RPE with time (linearity observed via visual inspection of data - not discussed by authors).
Eston et al. (2007)	10 physically active males	Incremental exercise test performed prior to first cycling task	3 constant load cycling tasks to exhaustion performed in fatigued (x1) and control (x2) conditions	Borg 15-point RPE scale	No significant difference in the rate of increase of RPE between fatigue and control conditions when time is expressed as %. RPE concluded as exhibiting a scalar time property
Crewe et al. (2008)	7 well-trained male cyclists	Cycle ergometer test to determine peak power output	5 constant load cycling tasks performed to volitional exhaustion in hot (x2) and cool conditions (x3)	Borg 15-point RPE scale	Linear increase in RPE predicts duration of exercise to exhaustion at a fixed workrate in different ambient conditions (r = 0.97).

Authors	Participants	Familiarisation/ pre-testing session(s)	Exercise protocol	Scale	Key findings
Faulkner et al. (2008)	5 males and 4 females	Laboratory-based incremental treadmill test	Competitive half marathon race and 7-mile race	Borg 15-point RPE scale	No significant differences in RPE between races when time is expressed as %. Linear relationship between RPE and time.
Joseph et al. (2008)	i) 10 well-trained recreational cyclists (7 male, 3 female) ii) 10 well-trained recreational cyclists (7 male, 3 female)	i) Incremental VO_{2max} test and practice cycling time-trials at 2.5, 5 and 10km ii) Incremental VO_{2max} test and practice 5km cycling time-trial	i) Cycling time-trials over 2.5, 5 and 10km ii) 3 5km cycling time-trials performed in blinded hypoxic (x2) and control (x1) conditions	CR-10 scale	No significant differences in RPE at any relative distance within any trial. RPE concluded as exhibiting a scalar time property (observed via visual inspection of data).
Davies et al. (2009)	10 physically active males	Incremental VO_{2max} cycling test	Cycle task to exhaustion both prior to and 48 hours subsequent to an eccentric muscle damaging protocol	Borg 15-point RPE scale	No significant differences in RPE between conditions when time is expressed as %. Evidence to support the scalar-linear relationship between RPE and exercise duration (observed via visual inspection of data).
Swart et al. (2009)	i) 12 well-trained competitive cyclists ii) 6 well-trained recreational cyclists	Incremental VO_{2max} cycling test and familiarisation with RPE scales	i) 5 40km cycling time-trials: feedback withheld during trials 1-4 except for completed distance; all feedback during trial 5 withheld until final km ii) 4 time-trials over 5, 10, 40 and 100km	i) Borg 15-point RPE scale ii) CR-10 scale	i) Increase in linearity of RPE over time across first 4 trials. Reduced linearity in Trial 5 attributed to withheld feedback. ii) RPE during 5km trial was significantly higher than during 40 and 100km trials.

Authors	Participants	Familiarisation/ pre-testing session(s)	Exercise protocol	Scale	Key findings
Pereira et al. (2011)	8 male team games players (basketball, football and volleyball)	Participants established maximum jump height and performed practice test of 40 jumps and familiarised with RPE scale	3 jumping tasks performed on separate days, with designated rest periods of s, 5 s and 6 s	Borg 15 point RPE scale	Linear relationship reported between adjusted RPE data and jumps completed (based on comparison of linear and quadratic regresseion models).
Swart et al. (2012)	7 trained competitive male cyclists	Incremental VO2max cycling test, familiarisation time-trial and familiarisation with RPE and TEA scales	2 100km time-trials: i) self-paced maximal time-trial incorporating 5 maximal effort 1km sprints; ii) submaximal (70% peak power) 100km time-trial incorporating 5 maximal effort 1km sprints	Borg 15 point RPE scale and TEA scale	Linear increase in RPE during maximal time-trial (observed via visual inspection of data). TEA scores were disassociated from RPE scores following maximal effort sprints.

Noakes (2004) analysed data from a previously published study by Baldwin et al. (2003), whereby participants performed two submaximal cycling trials to volitional exhaustion in both a glycogen-depleted and glycogen-loaded state. Although participants were able to cycle for 34% longer in the glycogen-loaded state, the linear relationship between RPE and task duration was evident in both conditions. In addition, when the RPE data points were re-plotted as a proportion of the total trial duration, the linear relationships for both trials overlapped. From visual inspection of the scatter-plots, linearity appeared to be established via a linear regression of the group mean data, although no specific method of statistical analysis was reported. A key conclusion emanating from this study focused on the potential impact of a subconscious glycogen signal informing the conscious RPE response. It has been postulated that if exercise was solely limited by the depletion of energy substrates, then RPE responses in fixed work-rate tasks of this nature would be characterised by a rapid increase towards the end of the exercise bout when glycogen stores were depleted to critically low levels (Tucker, 2009). As such, these findings were provided as evidence in support of the CGM theory of exercise regulation (Noakes, 2004).

A study by Eston et al. (2007) explored the influence of antecedent fatigue on RPE responses in a subsequent cycling task. Participants were required to complete a total of three constant load cycling trials to volitional exhaustion, the first of which was performed in a fatigued state, with participants having undertaken a prior bout of exhaustive exercise. The remaining two trials were performed at the same workload, but in a non-fatigued state. Raw RPE values were regressed against time for the three trials, and revealed the rate of RPE increase to be significantly higher in the fatigued condition. Similarly to the findings of Noakes, no significant differences in perceptual responses were observed between conditions when time was expressed as a proportion of the total duration. This led the authors to conclude that RPE was set at the beginning of the exercise task using a scalar internal timing mechanism, and that RPE could therefore be used to predict the duration of an exercise bout. The analysis of the raw RPE data for all participants was in contrast to the mean values utilised by Noakes (2004). As such, an appreciation of the pattern and spread of data can be gleaned from visual inspection of the scatter plots. However, the authors did not indicate as to whether alternative models such as a polynomial regression were tested in order to establish the most appropriate fit. Furthermore, there was a degree of ambiguity regarding the precise method used to establish the scalar time property of RPE, as the authors describe regressing the RPE values for each individual, yet appear to present a regression based on the group responses.

Whilst the studies by Noakes (2004) and Eston et al. (2007) centred on relationship between RPE and exercise duration, Garcin et al. (1999) focused on whether or not participants could consciously predict exhaustion time, by utilising the ETL scale in addition to RPE during an incremental cycling task to volitional exhaustion. Linear regressions revealed that ETL values rose linearly up to the ventilatory threshold (VT) ($r = 0.99$; $p < 0.01$), but a steeper rate of increase in ETL response was observed above the VT. As such, the ETL scale was deemed inappropriate for incremental exercise above the VT. However, no statistical results were reported for ETL responses above VT, and the relationship between RPE and duration was not discussed. Based on previously observed RPE values at VT, the authors proposed an expected lower limit of RPE and ETL values that would be expected at this time point (RPE $\leq$ 14; ETL $\leq$ 8). When comparing the values at VT, 21.5% of participants recorded RPE of $\leq$ 14, whereas 15.6% recorded ETL of $\leq$ 8. However, when the two scales were combined, less than 10% of participants recorded values of $\leq$ 14 (RPE) and $\leq$ 8 (ETL). The authors therefore concluded that the combination of RPE and ETL could provide a more precise detection of the VT than either measure used in isolation. However, the practical application of this proposal is unclear. It is plausible that, at a given time point, a performer may simultaneously provide contrasting RPE and ETL responses in relation to the respective values expected at VT (for example, RPE > 14 and ETL < 8). In this instance, it is not clear which scale would provide the best detection of VT, and therefore whether the perception of exertion should supersede the estimation of time remaining, or vice versa. Moreover, the different rates of increase between RPE and ETL, and their respective relationships with time, may create further problems when attempting to use both measures in conjunction to predict VT.

Further investigation into the utility of the ETL scale studied the effect of fitness levels on RPE and ETL responses obtained at 2-minute intervals throughout a constant speed running task to exhaustion (Garcin et al., 2004). In addition, the authors sought to explore whether RPE and ETL responses in the early stages of the trial (recorded at 2 and 4 minutes) could be used to predict exhaustion time. Despite a degree of ambiguity in the presentation of some results significant correlations were evident between the proportion of task duration and RPE ($r = 0.54$ to 0.84; $p < 0.01$) and ETL ($r = 0.58$ to 0.61; $p < 0.01$). However, linear extrapolation of RPE and ETL values obtained at minutes 2 and 4 of the running trial were not found to predict exhaustion time. This finding contrasts with the conclusions presented by Noakes (2004) and Eston et al. (2007), which postulate that RPE responses could be utilised to predict the end-point of an exercise task. In addition, the findings of Garcin et al. (2004) have received less attention in related literature, and possibly detract from the argument in support of the CGM model of exercise regulation.

Whilst the vast majority of previous literature has focused on prolonged running and cycling tasks, Pereira et al. (2011) explored patterns of RPE response in an intermittent vertical jumping protocol. The participants performed three vertical jumping tasks, involving repeated jumps at 95% of their maximal jump height until they were unable to reach the target. RPE was recorded throughout and plotted as a proportion of the total exercise duration. In order to establish the most appropriate fit to their data, the authors applied both a linear and quadratic regression model to their findings. With the linear model demonstrating the best fit, a comparison of the regression slopes showed no significant difference between conditions. The authors then opted to combine the data to produce one slope for all three conditions. This was then re-plotted as 'adjusted' data that illustrated a linear relationship. It was therefore concluded that RPE could act as a predictor of duration in intermittent jumping activities. However, the manipulation of the data creates some confusion with regard to this key finding. The linear slopes presented on the 'adjusted' data conflict with visual inspection of the 'raw' data, which suggests a more curvilinear trend for two of the jumping tasks. In addition, no method was used to establish whether significant differences were evident for the RPE values obtained at each time point across the three conditions. Moreover, it was not specified whether other regression models were tested for goodness of fit alongside the linear and quadratic models. Indeed, had a higher order polynomial regression provided a better fit than the quadratic function, much of the subsequent analysis would have been rendered superfluous. In addition, although team games players were recruited for this study, the participants had received no specific training in jumping activities. Unaccustomed exercise involving repeated eccentric muscle activations, such as multiple jump landings, is typically associated with increased muscle damage (McHugh et al., 1999). As such, the performance of ~100 jumps during the task may well have induced muscle damage in some of the participants. Whilst each testing session was separated by a minimum of 72 hours, this may have been insufficient time for the associated performance impairments and symptoms of muscle soreness to subside (Marginson et al., 2005) and may have consequently impacted upon both jump performance and RPE responses.

An alternative approach to analysing patterns of RPE response was provided in an analysis of five 40 km self-paced cycling time-trials (Swart et al., 2009). During the first four trials, all feedback except for completed duration was withheld from the participants. During, the fifth trial, all feedback including completed distance was withheld until the participants had completed 39 km, when they were informed that they had 1 km remaining to complete (unknown time-trial [UTT]). Significant differences in RPE response were reported between trial one (T1) and trial four (T4) and also between T4 and UTT. The RPE values for the first four time-trials demonstrated a non-linear pattern of increase in relation to distance completed, with all trials exhibiting a noticeably steeper increase in RPE during the latter stages of each trial. Given the self-paced nature of the time-trial, this late burst is consistent with the end-spurt phenomenon described previously. In addition, the observed pattern of increase of RPE during T4 differed from that observed for UTT. In an attempt to quantify the extent of linearity of these relationships, the authors calculated and plotted a linear regression line to the data for each of the five trials. In addition, they plotted a 4^{th} order polynomial regression (determined as the most appropriate fit for RPE vs. time) over the linear regression line. A 'linearity score' was achieved by calculating the sum of residuals (root of differences squared) of the deviation of the polynomial curve from the linear regression (thus a lower score indicating greater linearity). Linearity was found to improve with experience, with progressively lower scores reported from T1 to T4. However, a substantial reduction in linearity was evident from T4 to UTT, attributed to the increased uncertainty of the completed distance. The linearity scores also demonstrated a significant relationship with mean power output of the time-trials (r =

0.95; $p < 0.01$). These findings led the authors to conclude that greater linearity resulted from increased experience of the task, leading to the implementation of a more effective pacing strategy that in turn enabled a better performance. This would appear to provide additional support for the CGM theory of exercise regulation, and is further borne out by the reduced linearity reported for UTT, where all feedback was withheld from participants until the final 1 km. This would suggest that the uncertainty led to a more conservative pacing strategy, and therefore a sub-optimal time.

2.6.1. Conclusions from research into the predictive capacity of RPE

It is evident from the current literature that there is a lack of a consistent method for establishing the capacity of perceptual measures to predict exercise duration. Whilst some studies provide basic correlations in conjunction with visual inspection of the data in order to establish relationships between the variables (Noakes, 2004; Crewe et al., 2009), other studies adopt a more complex approach, utilising various regression analyses to explain findings (Eston et al., 2007; Faulkner et al., 2008; Pereira et al., 2011). Additionally, some studies compared raw data from all participants (Eston et al., 2007; Faulkner et al., 2008), whereas others opted to analyse group mean data (Noakes, 2004; Crewe et al., 2009; Swart et al., 2009). Moreover, there is also a degree of ambiguity when comparing the descriptions of some statistical methods with the eventual results, and a lack of consistent terminology is apparent between studies. Although some of the methods outlined in Table 2.2 may demonstrate greater complexity in their analysis, this does not necessarily translate into a clearer message that enables greater ease of understanding. When deciding upon the most appropriate method of data analysis, it is therefore important to remember the primary research question. In practical terms, the area of focus within this thesis is concerned with whether self-perception can accurately predict exercise duration. In this respect, it can be argued that the more complex methods of analysis outlined above do not provide any additional insight over and above visual inspection of the descriptive data. For example, whilst the manipulation of data in the study by Pereira et al. (2011) allowed the authors to report findings that were consistent with established concepts presented by much of the related literature, their approach arguably provides a simplified and somewhat misleading picture of the nature of the relationship between RPE and exercise duration during intermittent jumping exercise.

Despite the methodological differences between studies, an overriding theme evident across all of the reported findings is the potential capacity of perceptual measures to predict exercise duration. The bulk of existing research to explore this relationship has focused on prolonged running and cycling tasks, with majority of findings appearing to support the concept of self-perception as a predictor of time to exhaustion. However, this has not been supported by all studies, as evidenced by the findings from Garcin et al. (2004). In addition, the recent study of vertical jumping (Pereira et al., 2011) tasks has also produced some questionable findings in this regard. Many of the studies outlined in Table 2.2 used endurance-trained participants, or failed to specify training background. It is plausible that performers with greater prior experience of a certain mode of training may be more adept at utilising self-perception to regulate performance. As a consequence of their prior experience, endurance trained participants will potentially have greater familiarity with the sensations of exertion arising from prolonged cycling or running activity than recreational athletes or team games players. It could therefore be argued that studies involving endurance-trained participants performing a relatively familiar endurance-based task would exhibit a stronger linear relationship between RPE and exercise duration than if the study had been conducted with novice performers. Indeed, Swart et al. (2009) demonstrated that even well-trained cyclists produce an increasingly linear pattern of RPE responses as they benefit from greater experience of a cycling time-trial.

Although Garcin et al. (2004) concluded that fitness level did not impact upon the capability of self-perception to predict exercise duration, it should be noted that fitness level is not necessarily reflective of prior experience. As such, the strength of this relationship in novel or alternative modes of exercise has yet to be established. Furthermore, given the wide-ranging factors that contribute to RPE (Noble and Robertson, 1996), it is plausible to expect that manipulation of one or more factors could lead to a subsequent disruption of exercise regulatory capabilities. Studies that have manipulated glycogen levels (Noakes, 2004), fatigue levels (Eston et al., 2007), environmental conditions (Crewe et al., 2009), muscle damage (Marcora and Bosio, 2007; Davies et al., 2009) and deception of distance feedback (Albertus et al., 2005) were found to have no effect on the observed linear relationship between RPE and duration, suggesting that, in these instances, the performers were able to accurately interpret afferent feedback and adapt pacing accordingly. However, this list is far from exhaustive, and other examples could provide greater disturbance to perceptual capabilities. An instance of synovial joint injury such as an ACL rupture could provide a heightened example of a disturbance to perceptual mechanisms, where the combination of injury, surgery and associated de-conditioning of the surrounding musculature may disrupt homeostasis and thus provide altered sensory feedback.

2.7. THE IMPACT OF INJURY AND SURGERY ON SELF-PERCEIVED KNEE-JOINT PERFORMANCE

ACL injury is prevalent in multi-sprint sports including basketball, soccer and American Football (Magnussen et al., 2009), with a rupture typically occurring during athletic movements such as landing or changing direction, where the knee is placed under extreme translational and rotational stress (Griffin et al 2006; Quatman et al., 2010). Evidence suggests that the majority of individuals who have suffered an ACL injury will experience knee instability upon their return to previous activity levels and will, therefore, require surgery (Hurd et al., 2008). There are an estimated 80,000-250,000 ACL injuries (Griffin et al., 2006) and approximately 100,000 ACL reconstructive surgeries performed annually in the US (Brown and Carson, 1999). The cost of ACL reconstructive surgery and associated rehabilitation has been estimated at over $17,000 (Paxton et al., 2010), with total costs of surgery approaching an estimated $1 billion per year (Flynn et al., 2005). Although return to full activity is estimated at 6-9 months following surgery (Beynnon et al., 2005), a study by Ardern et al. (2011b) identified that 67% of patients have not returned to competitive sport by 12 months post-surgery. In order to achieve an optimal recovery time, a patient is required to adhere to a progressive rehabilitation schedule, comprised of a variety of exercise modalities (an example schedule of rehabilitation is presented in Figure 2.2). Given that most ACL-reconstructed patients will only benefit from limited contact time with a physiotherapist (Coppola and Collins, 2009), it therefore becomes important for patients to be able to accurately self-perceive changes in physical capability. If a patient's self-perceived knee function provides an underestimation of their functional capabilities, then this might lead to an overly cautious approach to their rehabilitation and possibly prompt a sub-optimal performance due to premature cessation of discrete exercise bouts. The cumulative effect of multiple sub-optimal sessions performed over a sustained period may result in an extended rehabilitation and ultimately delay return to sport. Considering the implications of increased treatment costs and extended absence from competitive sport, it is desirable for patients to optimise their rehabilitation and accelerate the recovery process whilst avoiding re-injury to the knee. However, the process of initial trauma, through to the surgical intervention and rehabilitation creates an inevitable disruption to the knee joint that might subsequently impact upon self-perceived capabilities and the associated implications for exercise regulation. These potential disruptions are detailed in subsequently.

2.7.1. Impact of surgical intervention

2.7.1.1. Method of reconstructive surgery

There are a number of available methods for ACL reconstructive surgery, with the choice of replacement graft depending on factors such as the patient's activity levels and the expertise and preference of the surgeon (West and Harner, 2005). The most common surgical methods involve the harvesting of donor tissue from the patella tendon or semitendinous tendon (Wright et al., 2010). The patella tendon is the common tendon for the quadriceps muscle group (comprising the rectus femoris vastus lateralis, vastus medialis and vastus intermedius muscles) that act as extensors of the knee joint (Floyd, 2007). A bone-patella tendon-bone (BPTB) graft utilises the central third of the patella tendon with adjacent bone blocks from the tibia and femur (Kousa et al., 1995). It is suggested that the bone-to-bone fixation promotes an increased rate of healing in comparison to semitendinosus grafts (Carmichael and Cross, 2009). One drawback to this procedure is evidence of a trend towards patellofemoral joint pain in patients (Forster and Forster, 2005). In addition, the disruption to the patella can lead to incidences of pain when kneeling (Aune et al., 2001). The semitendinosus is part of the hamstrings muscle group (also comprising the biceps femoris and semimembranosus muscles) that acts to flex and also medially rotate the knee (Hamill and Knutzen, 2003). A semitendinosus graft may be less painful than the BPTB graft (Goldblatt et al., 2005). However, reduced power in the hamstring musculature has been reported in patients who have undergone this method of reconstruction (Forster and Forster, 2005). Given the important role fulfilled by the semitendinosus in reducing tibial translation and rotation, this procedure is less favoured for athletes who require dynamic stability of the knee during sporting actions (Carmichael and Cross, 2009). Whilst there is agreement that BPTB and semitendinosus grafts provide similar functional outcomes (Forster and Forster 2005; Herrington et al., 2005; Krych et al., 2008), both procedures provide an inevitable disturbance to the respective donor tendon, and also weakness in the involved musculature (Yasuda et a., 1992; Forster and Forster, 2005). The patient has to interpret any subsequent changes in afferent feedback relating to tension and pain, and integrate these with other perceptual cues in order to form a perceptual response from which to make accurate judgments pertaining to work-rate and pacing.

2.7.1.2. Changes to ACL sensory function

A number of mechanoreceptors are present in an intact ACL that serve to provide sensory feedback, and help to inform decisions about positioning and movement of the knee joint (Solomonow, 2006). Activation of these nerve fibres (detailed in Table 2.3) may influence activity in the surrounding musculature to help provide stability (Duthon et al., 2006).

Table 2.3 Sensory receptors present in the ACL

Receptor	**Description**
Ruffini receptors	Sensitive to stretching and provide information on static joint position, intra-articular pressure and amplitude and velocity of joint rotations (Enoka, 2002).
Golgi Tendon-like receptors	Located near the attachments of the ACL, and provide information on changes in tension, particularly at extremes ranges of movement (Schultz et al., 1984).
Vater-Pacini receptors	Sensitive to rapid movements and are therefore able to detect acceleration and deceleration of a joint (Solomonow and Krogsgaard, 2001).
Free-nerve endings (nociceptors)	React to abnormal deformation of tissues, such as compression and stretching, and provide sensations of pain (Solomonow and Krogsgaard, 2001).

Although receptors present in the ACL only form a small proportion of the total number of mechanoreceptors found in the entire knee joint (Hogervorst and Brand, 1998), there is evidence to suggest that they fulfil an important role in producing a ligamento-muscular protective reflex. Pulling the ACL has previously been found to elicit an excitatory reflex in animal hamstring muscles (Solomonow et al., 1987; Miyatsu et al., 1993; Raunest et al., 1996). In human cases, direct electrical stimulation of the ACL has been found to produce an excitatory response in the hamstring muscles, with an estimated latency ranging between 50-180 ms (Dyhre-Poulsen and Krogsgaard, 2000; Tsuda et al., 2001). In other instances, the application of anterior tibial shear force has also been found to elicit a muscular response from the hamstrings (Beard et al., 1993; Friemert et al., 2009). It has been theorised that the latency of this reflex response is too slow to produce sufficient muscular force to prevent injury (Dyhre-Poulsen and Krogsgaard, 2000; Duthon et al., 2006). It is therefore proposed that the sensory input from the mechanoreceptors in the ACL act as part of a feed-forward motor control mechanism, comprised of afferent information from a range of sources that could include the involved musculature and visual feedback (Krogsgaard et al., 2002). Whilst it difficult to differentiate the contribution of the ACL from the afferent feedback provided by other knee joint structures and the surrounding musculature (Friemert et al., 2009), individuals with ruptured ACLs have displayed significantly increased reflex latencies, with mean values of 98.8 ms vs. 52.7 ms for injured and non-injured limbs, respectively (Beard et al., 1993). More pertinently, it has been suggested that a reconstructed ACL is not fully re-innervated and that the ligamento-muscular reflex is not restored to its pre-injury level (Krogsgaard et al., 2011).

The reduced sensory feedback from a replacement graft may also be linked with changes in joint position sense that have been reported in ACL-reconstructed knees following reconstructive surgery (Katayama et al., 2004). These changes suggest an impaired ability to replicate joint angles, which may have associated implications for the performance of sport-specific movement skills such as landing and changing direction. However, the clinical relevance of the magnitude of the errors in angle replication has recently been questioned (Gokeler et al., 2012).

2.7.2. Post-operative rehabilitation

Post-operative rehabilitation needs to strike the correct balance between restoring knee joint and muscle function, without compromising the integrity of the reconstructed ACL as it undergoes the lengthy process of ligamentisation (Marumo et al., 2005). This healing process consists of initial necrosis of the donor tissue, followed by revascularisation and remodelling of the graft (Ntoulia et al., 2011). Immediately post surgery, the replacement graft has a tensile strength greater than that of the original ACL (Grodski and Marks, 2008). However, the graft then progressively weakens as a consequence of tissue degeneration and micro-ruptures due to a lack of blood supply (Tohyama et al., 2009). Revascularisation commences with the formation of new blood vessels evident at 8-weeks post-surgery (Clancy et al., 1981). This prompts a remodelling phase that enables the graft to develop biological and biomechanical characteristics that resemble an intact ACL, in a process that may take longer than 2 years (Janssen et al., 2011). It is hypothesised that the combination of the revascularisation process and the progressive increase in stress provided by the rehabilitation programme causes the new graft to adapt and increase in strength (Beynnon, 2005). However, if a rehabilitation programme is too aggressive, it could compromise the integrity of the ACL graft, resulting in increased knee laxity (Marumo et al., 2005). The challenge for the patient is to therefore optimise the rehabilitation process in order to achieve an expeditious return to full activity whilst minimising undue strain to the reconstructed ACL.

An example post-operative ACL rehabilitation programme is presented in Figure 2.2. During the early post-operative stages, a primary aim is to commence quadriceps and hamstring exercise in order to limit muscle atrophy (Kvist, 2004; Grodski and Marks, 2008; van Grinsven et al., 2010). This is initially achieved through isometric (static) closed chain (0° to 60° knee flexion) and open chain (40° to 90° knee flexion) exercises without additional loading, performed in a restricted range of motion in order to minimise strain on the graft (Grodski and Marks, 2008; van Grinsven et al., 2010). Another important aim of early post-operative rehabilitation is to reduce swelling and inflammation around the knee (van Grinsven et al., 2010). Swelling has been implicated in muscle atrophy, potentially due to producing an inhibitory mechanism (Hopkins and Ingersoll, 2000; Rice and McNair, 2010). Additionally, inflammation provokes stimulation of free nerve endings resulting in an increased pain response that may also contribute to muscle inhibition (Rice and McNair, 2010). Attention is also focused on the restoration of range of motion during this initial phase of rehabilitation, due to proposed benefits in reducing pain and patellofemoral problems, and enabling a normal gait pattern (van Grinsven et al., 2010). Achievement of the required goals of a given phase is a prerequisite for advancing onto the subsequent stage of rehabilitation, with increases in intensity determined by the patient's response to training and the levels of pain and swelling that they experience (van Grinsven et al., 2010). As knee function is gradually restored, exercise becomes progressively more dynamic with a return to straight-line running within 2 to 3 months (Kvist, 2004). However, at this corresponding phase of rehabilitation, the ACL graft has yet to complete the revascularisation process (Ntoulia et al., 2011) and demonstrates substantially increased laxity (Beynnon et al., 2005). A risk during this stage is that an increased level of patient confidence in their knee function may prompt an overly aggressive approach to their rehabilitation, thus compromising the integrity of the graft by exposing it to avoidable trauma (Stanish and Lai, 1993). Conversely, a fear of re-injury evident amongst some patients may prompt an avoidance of more dynamic modes of exercise and ultimately result in a sub-optimal approach to their rehabilitation (Heijne et al., 2007). A further consideration is that changes in knee function following ACL surgery are not immediately perceived by patients, but are instead noticed subsequent to 'testing' the knee in functional activities (Gleeson et al., 2008a). Given that self-perceived performance capabilities may be integral to the pacing process, latency in acknowledging functional improvements may also prompt the application of an inappropriate pacing strategy to rehabilitative tasks.

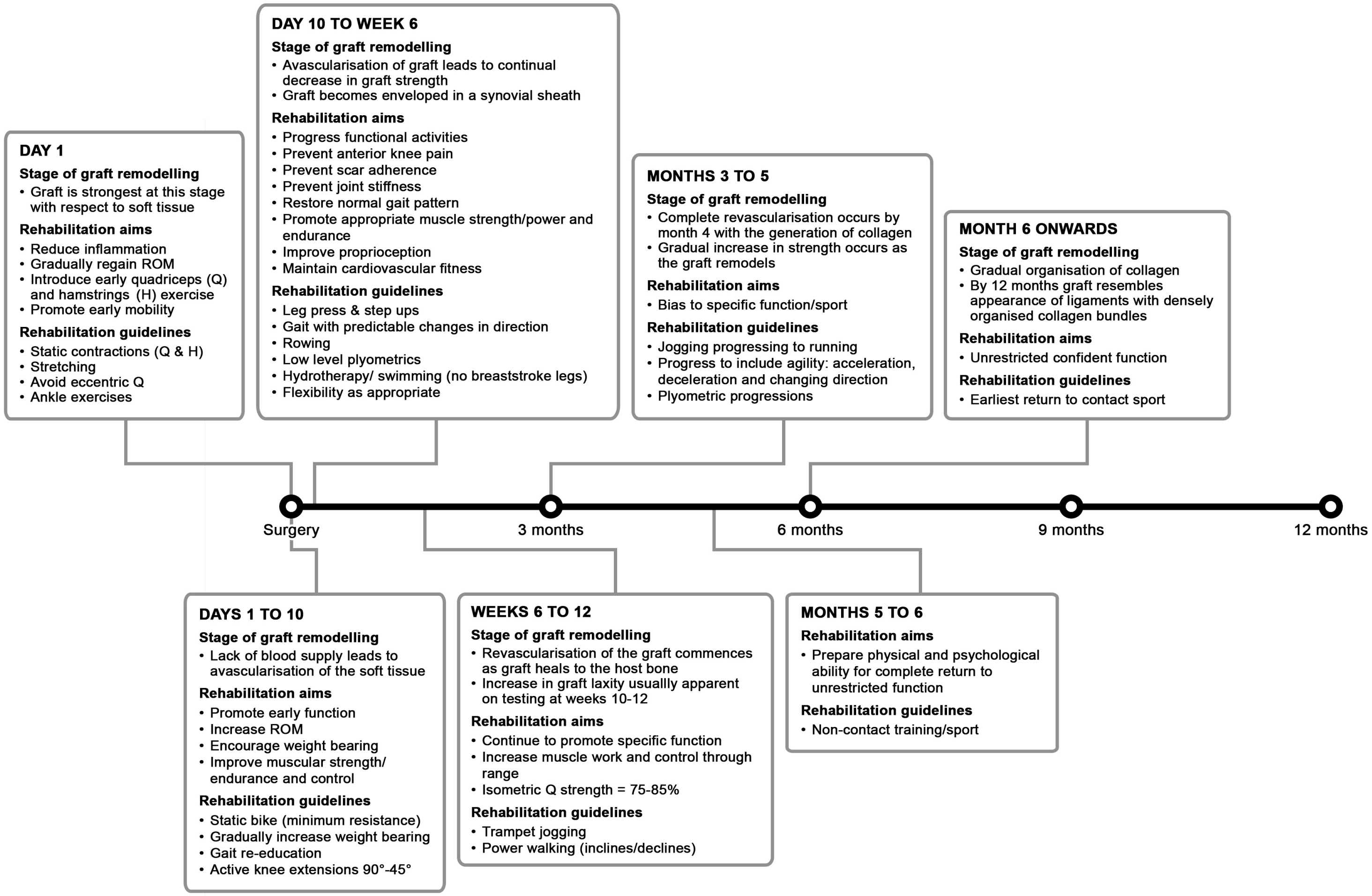

Figure 2.13 Timeline of example post-operative ACL rehabilitation schedule (adapted from R.J.A.H. Orthopaedic and District NHS Trust, 2007)

2.7.2.1. Re-education of muscle recruitment patterns and motor skills

It has been theorised that low levels of hamstring activity allied to high levels of quadriceps activity during landing and cutting activities may produce displacement of the tibia and consequently increase risk of ACL injury (Griffin et al., 2006). With increased hamstring activation having been demonstrated to reduce strain on the ACL (Fleming et al., 2005), a coordinated co-activation of the hamstrings and quadriceps muscles may therefore be important in reducing potentially harmful motions and loadings on the knee joint (Alentorn-Geli et al., 2009). Video analysis has estimated that ACL injuries occur <50ms following initial ground contact (Krosshaug et al., 2007). Consequently, it has been proposed that this time-frame is insufficient for individuals to generate force, and that instead muscles are recruited in anticipation of a given movement using a feedforward mechanism (Hewett et al., 2005). During post-operative ACL rehabilitation, focus is given to the re-education of optimal muscle recruitment patterns and motor skills, with the aim of developing anticipatory hamstring muscle activation prior to jump landing activities (Fagenbaum and Darling, 2003). Indeed, athletes with a history of ACL injury have been shown to exhibit increased hamstring activation during landing and direction changing, attributed to subconscious adaptations to motor programs and muscle recruitment patterns (Riemann and Lephart, 2002). Several intervention studies support the notion that re-educating the knee joint and developing optimal movement patterns may substantially reduce risk of ACL injury (Myklebust et al., 2003; Mandelbaum et al., 2005; Olsen et al., 2005).

The selection of surgical procedure, as discussed previously, may present additional implications for the patient with regard to muscle recruitment and motor skill development. Given their role in reducing anterior translation and lateral rotation of the tibia, a semitendinosus tendon graft may compromise the effectiveness of the hamstrings as dynamic stabilisers of the knee joint (Bonci, 1999). Ultrasonic investigations have found that the semitendinosus tendon is only fully regenerated after 18 months post surgery (Papandrea et al., 2000). Moreover, there is some disagreement over the nature of restored hamstring function following ACL surgery, with the suggestion that this is due to increased hypertrophy of the bicep femoris and semimembranosus muscles, thus compensating for a weakened semitendinosus (Nikolaou et al., 2007). As a consequence, the precise contribution of each of the hamstring muscles to various joint actions may differ between the reconstructed and contralateral limb, thus prompting individual muscles to fatigue at a different rate. It is therefore important for the patient to be able to accurately interpret the resulting sensory feedback from the knee joint in order to adjust work-rate prior to any potential disruption to homeostasis.

As previously highlighted, performance decrements as a consequence of fatigue are implicated in an increased risk of injury. This risk is exacerbated during rehabilitation from ACL-reconstructive surgery, due to the laxity of the replacement graft throughout the intermediate stages of the recovery process. Previous research has shown jump landing techniques to be adversely affected by fatigue, with the implication that the resulting sub-optimal knee and hip biomechanics could potentially increase ACL injury risk (McLean and Samorezov 2009). This is further supported by evidence of increased anterior tibial translation subsequent to fatiguing exercise of the knee musculature (Wojtys et al., 1996). Furthermore, acute fatiguing activity has also been shown to significantly reduce hamstring muscle activity in direction-changing manoeuvres (Zebis et al., 2011). It has also been postulated that fatigue compromises the proprioceptive capabilities of the knee joint (Hiemstra et al., 2001), as evident in reduced knee joint position sense following an acute bout of fatiguing exercise (Givoni et al., 2007; Ribeiro et al., 2007; Ribeiro et al., 2011). Moreover, there is the suggestion that the fatigue-induced impairments to knee joint kinematics may still be evident following forty minutes of recovery (Tsai et al., 2009).

A study by Borotikar et al. (2008) explored the effects of fatigue upon single-leg landings, by alternating landings with a series of squats. This process was continued until the participants were unable to perform three consecutive squats unassisted (task failure). Whilst technique was found to be significantly impaired at the point of task failure, similar impairments were evident at 50% of the trial duration. This finding indicates that a reduction in performance and an associated increase in ACL injury risk occur considerably earlier than the point of task failure, and further emphasises the need for patients to be able to accurately anticipate the onset of fatigue, and pace their rehabilitation accordingly. In this regard, the prediction of exercise duration may be important to identify a critical point at which fatigue begins to significantly impair performance.

Given the risk of impaired knee joint mechanics and muscle recruitment as a consequence of fatigue, it is especially important for a patient to able to pace their rehabilitation and anticipate these reductions in performance, particularly in view of the altered sensory feedback that may be provided by the ACL-reconstructed knee in comparison to the contralateral limb.

2.7.2.2. The re-introduction of dynamic exercise

The re-introduction of dynamic exercise into an ACL rehabilitation programme may result in exercise-induced muscle damage (EIMD), whereby acute microtrauma is sustained to the involved musculature (McHugh et al., 1999). The associated changes to contractile and neural components of muscle performance may affect RPE during subsequent exercise endeavours. EIMD results from eccentric muscle activations during exercise that is either unaccustomed or of substantially increased intensity or duration (Byrne et al., 2004), and has been observed following bouts of resistance training (Paul et al., 1989; Yamamoto et al., 2008), and plyometrics (Tofas et al., 2008; Twist et al., 2008) and running (Eston et al., 1995; Howatson and Milak, 2009). Progressive manipulation of these exercise variables and modalities is commonplace during an ACL rehabilitation programme (van Grinsven et al., 2010). EIMD is accompanied by elevated symptoms of soreness in the involved musculature (Proske and Morgan, 2001) that may provide an altered perception of exertion (Marcora and Bosio, 2007). These symptoms are caused by an inflammatory response that initiates the regeneration process (Aoi et al., 2004; Byrne et al., 2004), whereby the breakdown of damaged tissue is thought to stimulate nociceptors and produce a sensation of pain (Proske and Morgan, 2001). The time-course of perceived soreness is typically characterised by minimal symptoms immediately following the exercise, with a subsequent increase in soreness that peaks between 24-48 hours before beginning to subside after approximately 72 hours (Marginson et al., 2005; Twist and Eston, 2005; Torres et al., 2010; Minshull et al., 2012). However, EIMD provokes an impairment to neuromuscular performance that follows a different temporal pattern, with reductions in strength and power evident prior to the onset of soreness (Byrne et al., 2001; Minshull et al., 2012). These findings would therefore suggest that perceived soreness does not always provide an accurate reflection of reduced neuromuscular performance capabilities, and may provide misleading feedback to the performer. An inability to accurately interpret the afferent cues resulting from muscle damage may have associated implications for self-regulating exercise.

Proske and Morgan (2001) theorise that the muscle damaging process begins with the over-stretching of sarcomeres during an eccentric activation. Eccentric muscle activations are capable of producing greater force (Westing et al., 1991; Webber and Kriellaars, 1997), yet exhibit lower motor unit recruitment (Bigland-Ritchie and Woods, 1976) in comparison to concentric activations. This places greater stress on the actinmyosin cross bridges, predisposing these structures to damage (Enoka, 1996). Whilst the myofilaments in the majority of sarcomeres are able to re-interdigitate, a small number will be terminally damaged (Proske and Morgan, 2001). The combination of non-functioning sarcomeres and damage to the excitation-contraction coupling system consequently results in a reduced ability to generate tension in the muscle (Morgan and Allen, 1999). This is evidenced by immediate and prolonged reductions in peak isometric force ranging between 25% and 70% (Rinard et al., 2000; Byrne et al., 2001; Brown et al., 2010; Minshull et al., 2012) and reductions in power output ranging between 15% and 65% (Byrne and Eston, 2001; Marginson et al., 2005; Minshull et al., 2012). It is theorised that impaired force production capabilities resulting from the onset of EIMD may lead to a subsequent reduction in dynamic joint stability, and potentially result in an increased risk of injury (Minshull et al., 2012). It is therefore important for individuals to perceive these changes in performance in order to regulate their training load and effectively manage the risk of injury. In accordance with the anticipatory CGM model of exercise regulation (Tucker, 2009), an inability to accurately judge levels of force during a given exercise bout may result in the subconscious selection of an inappropriate 'template RPE' against which to compare exercise demands. This may therefore have associated implications for the capability of RPE to predict exercise duration. Indeed, there is some evidence to suggest that the ability to accurately perceive levels of force production is impaired as a consequence of muscle damage. A study exploring the impact of EIMD on force replication ability of the forearm flexors discovered that participants overestimated the amount of force they were producing with the exercise-damaged arm (Saxton et al., 1995). However, when the force produced was express as a proportion of their daily peak force, it emerged that participants were generating the same relative force in comparison to their baseline measures. Comparable results were discovered by Proske et al. (2004), who observed similar errors in force replication following EIMD that were consistent in direction and magnitude with the previous literature. A study by Torres et al. (2010) also observed significantly impaired force replication capabilities in the knee extensors subsequent to EIMD. However, the direction of the error was not reported in this instance. These findings suggest that errors in the estimation of force production may be evident in the presence of EIMD.

The combination of reduced force production capacity and attenuated proprioceptive capabilities as a consequence of EIMD could have implications for dynamic joint stability and potential risk of re-injury during ACL rehabilitation. This places added importance on the ability to accurately interpret these changes in order to anticipate the onset of fatigue and regulate work-rate accordingly.

2.8. CONCLUSIONS

There is a growing body of research which suggests that RPE increases linearly in relation to exercise duration, and thus can be utilised as a predictor of end-point during incremental, constant work-load, and self-paced exercise. However, the range of methodologies and inconsistent terminology employed across these studies creates issues when attempting to compare results and establish the robustness of the findings. The majority of existing research has focused on running and cycling tasks, but it remains to be confirmed whether the predictive capacity of RPE is still evident in more novel and intermittent tasks that may have greater specificity to resistance training or rehabilitative exercise. The potential disruptions to perceptual cues subsequent to ACL reconstructive surgery also highlight the importance of being able to accurately self-perceive physical performance capabilities in order to regulate exercise with regard to optimising the rehabilitation process.

It has also been demonstrated that sensations of effort required to continue performing an exercise task can be separated from perceptions of exertion arising from the task (Swart et al., 2012). This distinction highlights a capability to produce an increased effort despite experiencing severe symptoms of exertion, as evident during an end-spurt in the latter stages of an endurance event (Abbiss and Pfeiffer, 2010). In this regard, it is plausible that a conscious prediction of the remaining task duration throughout an exercise bout may produce a different pattern of response in comparison to RPE. It is therefore worthwhile to explore different paradigms of self-perception (RPE and perceived task duration) in order to determine which scale provides the most accurate reflection of task duration during intermittent isolated muscle exercise. The resulting findings would then have implications for the regulation of exercise performance during resistance training and rehabilitative activities.

Chapter 3:
Relationships between self-perceived knee function and indices of musculoskeletal performance in an ACL-reconstructed population

CHAPTER 3: RELATIONSHIPS BETWEEN SELF-PERCEIVED KNEE FUNCTION AND INDICES OF MUSCULOSKELETAL PERFORMANCE IN AN ACL-RECONSTRUCTED POPULATION

3.1. ABSTRACT

The aim of this study was to explore the relationships between self-perceived measures of knee function and objective indices of musculoskeletal performance in an ACL-reconstructed population during various stages of post-operative rehabilitation, ranging from pre-surgery through to an anticipated completion of rehabilitation at 48 weeks post-surgery. Thirty-one ACL-reconstructed patients were assessed on five separate assessment sessions undertaken at pre-surgery, and 6 weeks, 12 weeks, 24 weeks and 48 weeks post-surgery. Self-perceived knee function was measured via the International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form and the Performance Profile (PP). Indices of musculoskeletal performance, including anterior tibio-femoral displacement (ATFD), peak force (PF) and rate of force development (RFD) of the knee extensors (KE) and the knee flexors (KF), and a single leg hop (HOP) for distance were also obtained. Correlation coefficients (Spearman rank and Pearson product-moment) revealed lack of significant correlations between self-perceived (IKDC and PP) and objective measures (ATFD, PF, RFD and HOP) throughout the early to intermediate stages (pre-surgery to 24 weeks) of post-operative ACL rehabilitation. However, significant positive correlations between IKDC and various indices of neuromuscular performance (PF_{KF}, RFD_{KE}, RFD_{KF}, HOP) became evident at 48 weeks ($r>0.41$; $p<0.05$). This disparity between self-perceived and actual knee function may reflect a lack of efficacy of the self-reported inventories (IKDC and PP), or possibly a misplaced level of confidence in the capabilities of the reconstructed knee.

3.2. INTRODUCTION

Rupture of the ACL is a serious and potentially career-threatening injury for sports performers that invariably requires reconstructive surgery to restore knee function (Hurd et al., 2008). The consequences of a performer sustaining an ACL injury involve incurring considerable hospital and physiotherapy costs (Paxton et al., 2010), coupled with an extended period of absence from competitive sport estimated at between 6 to 9 months (Beynnon et al., 2005). Despite this projected recovery process, an estimated 67% of patients do not return to competitive sport within 12 months of surgery, yet 85% of patients demonstrate normal or nearly normal knee function as rated by the IKDC (Ardern et al., 2011a). Possible reasons for this prolonged absence include a lack of confidence in the knee (Webster et al., 2008) and a fear of re-injury (Heijne et al., 2007; Ardern et al., 2011a). Indeed, perceived future self-efficacy of knee function (measured using a knee self-efficacy scale prior to surgery) has been reported as a strong predictor of long-term outcomes (Thomee et al., 2008). Considering that individuals with lower self-efficacy have been found to report higher levels of RPE during exercise tasks (Hu et al., 2007), it is plausible that these psychological factors may prompt an overly cautious approach to the recovery process by the patient, resulting in sub-optimal exercise regulation during rehabilitative exercise. The cumulative effect of multiple sub-optimal exercise sessions may preclude the patient from reaching required training goals, thus delaying progress onto the subsequent phase of rehabilitation (van Grinsven et al., 2010). This is an important consideration given that most patients will only benefit from limited contact time with a physiotherapist (fewer than 20 session during a post-operative ACL rehabilitation period that may last as long as 9 months), and will therefore have to perform the majority of rehabilitative exercise without specialist supervision (Coppola and Collins, 2009).

The process of ACL reconstructive surgery creates a substantial and necessary disturbance to various structures of the knee joint that may subsequently produce novel physical sensations for the patient. The most common approaches to ACL reconstruction involve the use of autografts utilising either the patient's patella tendon or semitendinosus tendon (Wright et al., 2010). The selected procedure will provide a substantial disruption to the donor tendon and associated weakness and atrophy in the quadriceps and hamstrings (Yasuda et al., 1992; Forster and Forster, 2005). Additional issues that may produce novel sensations can include altered sensory feedback from the replacement graft (Krogsgaard et al., 2011) and inhibited neuromuscular performance due to pain and swelling (Hopkins and Ingersoll, 2000; Rice and McNair, 2010). Prior experience is potentially an integral component in the generation of RPE and exercise regulation (Noble and Robertson, 1996; Tucker, 2009), with repeated exposure to an exercise task having been shown to result in an increased linearity in perceptual response accompanied by a concomitant increase in power output (Swart et al., 2009). In the instance of ACL injury and surgery, any novel physical sensations resulting from altered knee function might, therefore, create difficulties in accurately judging the demands of a given exercise task, and regulating work-rate accordingly. Self-regulation of work-rate is particularly important for patients undertaking rehabilitation sessions in the absence of specialist supervision. Given that many patients will only have periodic contact with a physiotherapist, the ability to accurately self-perceive physical capabilities is important in gauging progress towards a return to pre-injury activity levels. Indeed, self-reported measures of knee function are routinely used in a clinical environment to help monitor the progress of rehabilitation (Adams et al., 2012). It is, therefore, important to establish whether patients' self-perceived knee function relates to objective indices of their musculoskeletal performance.

There are a variety of rating scales and questionnaires designed to measure self-perceived knee function that typically require the patient to report their symptoms and functional limitations. These include the Cincinnati Knee Rating System (Borsa et al., 1998; Barber-Westin et al., 1999; Marx et al., 2001), the Lysholm Knee Rating System (Borsa et al., 1998; Marx et al., 2001), the Knee Outcome Survey Activities of Daily Living (Marx et al., 2001; Harreld et al., 2006), the International Knee Documentation Committee Subjective Knee Evaluation Form (IKDC) (Harreld et al., 2006; Gleeson et al., 2008a; Gleeson et al., 2008b), and the Knee Injury and Osteoarthritis Outcome Score (KOOS) (Thomee et al., 2007). Methods of validating these measures have included comparisons with previously validated scales (Higgins et al., 2007), the use of expert opinion from clinicians (Marx et al., 2001), and evaluation against clinical outcomes (Barber-Westin et al., 1999). Limited research has focused on precisely how these inventories relate to various objective measures of functional performance, such as muscle strength and unilateral jumping ability which are viewed as integral to successful rehabilitation and judging return to full activity. These indices of performance are often expressed in terms of the capabilities of the injured limb in relation to the non-injured limb, referred to as a limb symmetry index LSI (Borsa et al., 1998; Hopper et al., 2002; Ardern et al., 2011b; Thomee et al., 2011). Recommended LSI values include 85% (Ardern et al., 2011b), 90% Ageberg et al., 2008) and 100%Ardern et al., 2011b(Thomee et al., 2011), and those patients who demonstrate an acceptable level are more likely to return to sport (Fitzgerald et al., 2000; Ageberg et al., 2008; Ardern et al., 2011b). These objective measures, therefore, provide a relevant marker against which to compare self-perceived knee function.

Research into the relationships between self-reported and objective performance has tended to focus either on long-term outcomes of >12 months post-surgery (Ageberg et al., 2008; Ardern et al., 2011b) or relatively narrow periods within the rehabilitation process (Reid et al., 2007; Gleeson et al., 2008a; Gleeson et al., 2008b). For example, Ageberg et al. (2008) assessed patients in a long-term follow-up raging from 2 to 5 years (mean ± SD of 3 ± 0.9 years) after sustaining ACL injury. The authors reported low to moderate correlations (0.25–0.43) between self-perceived function (as measured through the KOOS inventory) and objective performance (knee extension, knee flexion, leg press and hop test score). Baseline pre-operative measures were not available for comparison, thus providing no scope for establishing how self-perceived function altered over the course of the rehabilitation in order to gauge progress. In contrast, Reid et al. (2007) examined relationships between the change scores for self-reported lower extremity function and single leg hop performance over a 6-week period, with baseline measures taken at 16 weeks post-surgery and a re-test performed at 22 weeks post-surgery. Similarly, low to moderate correlations (0.26 and 0.41) were again observed between the self-perceived function and the range of hop tests. Ardern et al. (2011b) highlighted a disparity between objective and self-reported measures, and the association with rates of patients returning to sport at 12 months post-surgery. Patients who displayed an acceptable LSI of >85% (n = 423; 84% of sample population) were found to be more likely to return to sport than those exhibiting an insufficient LSI of <85% (n = 80; 16% of sample population). However, patients reporting normal or nearly normal knee function via an IKDC (n = 468; 93% of sample population) were found to be no more likely than patients reporting poor function (n = 35; 7% of sample population) to attempt a return to competitive sport. The inconclusive results from these previous studies have implications for the validity of these self-reported inventories over the limited timescales utilised. This highlights a potential need for further investigation into the efficacy of these measures at additional time-points throughout the rehabilitation process, and also into possible alternative scales for self-reporting knee function.

The performance profile (PP) technique provides an alternative method of measuring self-perceived knee function (Doyle et al., 1998; Gleeson et al., 2008a; Gleeson et al., 2008b). Originally devised for use by athletes, coaches and sports psychologists (Butler and Hardy, 1992), the PP has since been adapted for use in a clinical setting with ACL-deficient and reconstructed individuals (Doyle et al., 1998; Gleeson et al., 2008a; Gleeson et al., 2008b). This method is based around selected principles of Personal Construct Theory (Kelly, 1955), which postulates that each individual's perception and understanding of events is generated by their unique set of personal experiences. The PP process requires the patient to identify and rate a number of key 'constructs' that they deem important markers of knee function. These terms and their associated meaning are unique to the patient, therefore, removing the potential problem of different interpretations between individuals. It is suggested that this method of recording self-perception of knee function may offer an effective tool to allow patients to monitor their own rehabilitation (Gleeson et al., 2008a), consequently increasing self-awareness of their rehabilitation and potentially improving adherence to programme. Indeed, PPs have been found to demonstrate significant positive correlations with important indicators of musculoskeletal performance, such as knee laxity and peak force, both prior to ACL-reconstructive surgery ($r = 0.68$ to 0.85) and 8 weeks subsequent to surgery ($r = 0.72$ to 0.82) (Gleeson et al., 2008b). The strength of these relationships would suggest that the PP is a viable alternative in comparison to traditional self-reported measures of knee function such as the KOOS or IKDC inventories. However, the efficacy of this technique has yet to be evaluated over a longer duration and at different stages throughout the ACL rehabilitation process.

The purpose of the present longitudinal study was to explore the relationships between self-perceived measures of knee function (IKDC and PP) and objective indices of musculoskeletal performance in an ACL-reconstructed population during various stages of post-operative rehabilitation, ranging from pre-surgery through to an anticipated completion of rehabilitation at 48 weeks post-surgery.

3.3. METHODS

3.3.1. Participants

An ACL-reconstructed population were recruited through the National Centre for Sports Injury Surgery (NCSIS), Robert Jones and Agnes Hunt Orthopaedic and District Hospital in Oswestry (n = 31). Twenty-seven males (age 31.6 ± 8.7 years; height 178 ± 6.9 cm; body mass 82.3 ± 10.7 kg) and four females (age 41 ± 4.8 years; height 166.5 ± 9.2 cm; body mass 74.4 ± 11.8 kg) gave their informed consent to participate in the study. Participants were selected sequentially from patients presenting with arthroscopically verified unilateral ACL rupture randomly admitted to the hospital over a 34-month period commencing in May 2007 through to March 2010. Approximately 70% of the ACL ruptures were sustained via non-contact mechanisms. The majority of injuries (~85%) occurred in a multi-sprint team sport environment, with the remaining 15% occurring during skiing. On average, participants had waited 12.4 ± 5.7 months following the initial injury before undergoing reconstructive surgery. Participants were scheduled to undergo one of two reconstructive surgery procedures (as determined by the orthopaedic surgeon): i) central third, bone-patella tendon-bone graft (n = 9); ii) semitendinosus and gracilis graft (n = 22). All surgical procedures were performed by the same consultant orthopaedic surgeon. Assessment protocols were approved by the Ethics Committees for Human Testing of Robert Jones and Agnes Hunt Orthopaedic and District Hospital NHS Trust.

3.3.2. Experimental procedures and design

Participants were assessed on five separate occasions. The first assessment session was scheduled prior to reconstructive surgery in order to establish baseline measures. Subsequent assessment sessions were undertaken at 6 weeks, 12 weeks, 24 weeks and 48 weeks following surgery. These post-operative assessments were scheduled to encompass key stages of progression across the rehabilitation programme. At each assessment session, participants completed self-perceived measures of knee function (detailed in section 3.2.3). Assessments of musculoskeletal performance, including anterior-posterior knee laxity, peak force (PF) and rate of force development (RFD) of the knee extensors (KE) and the knee flexors (KF), and a single leg hop for distance were obtained following completion of the inventories. Testing was performed on both the injured (INJ) and non-injured (NON) limbs, in a randomly-assigned counterbalanced order.

Following a standardised warm-up of five minutes cycle ergometry (~60 W, as tolerated by the participants depending on the progress of their rehabilitation) and an additional five minutes of stretching of the involved musculature, participants were secured in a seated position on a custom built dynamometer (Gleeson et al., 2008). The lever arm of the dynamometer was attached to the tested leg of the participant via a padded ankle cuff secured just proximal to the lateral malleolus and the lever arm was at an angle perpendicular to the tibia (Figure 3.1). The muscle action was localised through the use of adjustable strapping across the torso, pelvis and anterior thigh proximal to the knee joint. Throughout testing, the knee position was maintained at a functionally relevant angle of 25° (0.44 rad) (0° = full extension) which has been associated with the greatest mechanical strain on the ACL and a position of injury vulnerability during sports participation (Li et al., 1999) and identified for each participant during activation of the involved musculature using a goniometry system.

Participants were sat in an upright position with the knee of the opposite limb left unsecured at approximately 90° (1.57 rad) in order to reduce leverage during activation of the musculature of the tested limb (see Figure 3.1).

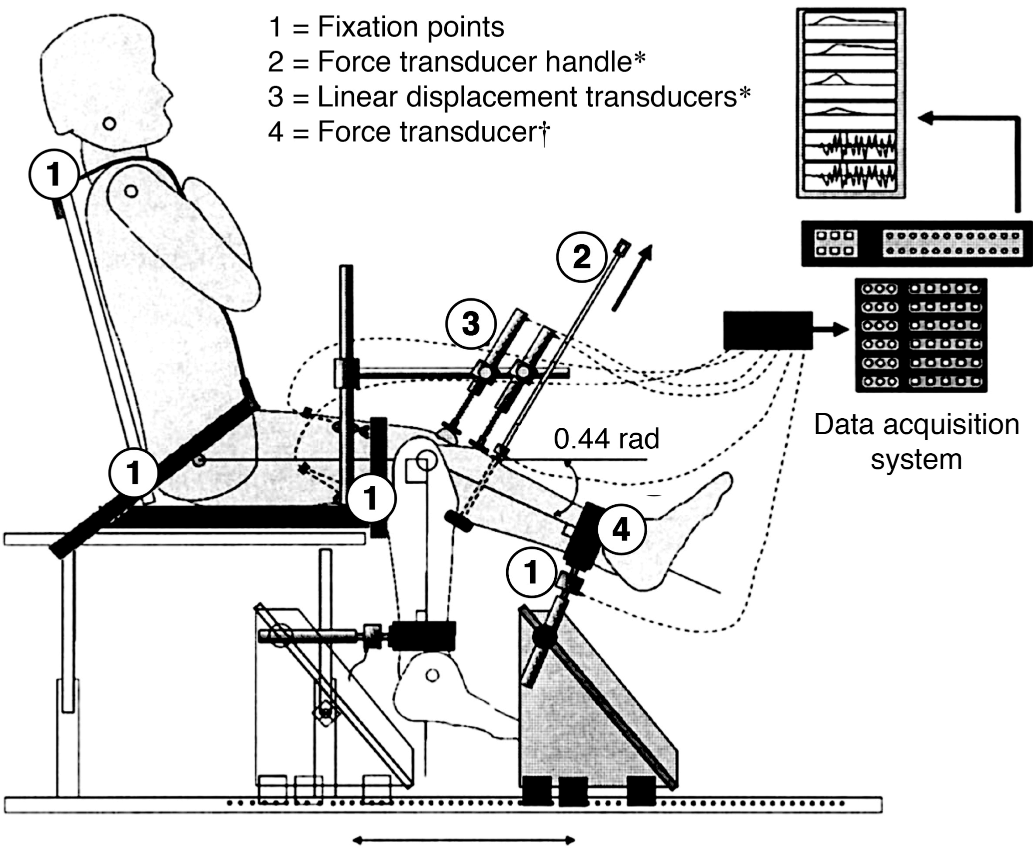

Figure 3.1 Schematic of participant and dynamometer orientation (adapted from Gleeson et al., 2008a)
*Measurement of ACL laxity
†Measurement of neuromuscular performance

3.3.3. Assessment of musculoskeletal performance

3.3.3.1. Knee laxity

Assessment of anterior tibio-femoral displacement (ATFD) to provide an estimate of knee laxity was performed using a custom built device (Gleeson et al., 1996). The orientation of the apparatus and participant are illustrated in Figure 3.1.

The device consisted of two linear inductive displacement transducers incorporating spring-loaded plungers (DCT500C, RDP Electronics Ltd., Wolverhampton, UK; 25 mm range). Both transducers were positioned perpendicular to the patella and tibial tuberosity and secured to the skin surface using tape to restrict movement to the anterior-posterior plane relative to the supporting framework. An anterior translation force was applied to the tibia via an instrumented force-handle incorporating a load cell (Model 31E500N0, RDP Electronics Ltd.; range 500 N). This device was positioned behind the leg at a level 20 mm inferior to the tibial tuberosity, with force applied in the sagittal plane in a perpendicular direction relative to the tibia. The transducers were interfaced to a computerised data acquisition system, with data sampled at 2.5 kHz (Cambridge Electronic Design Ltd., UK). An anterior tibial translation force of 160N was manually applied in the sagittal plane at a rate of $67 \pm 7 \text{ N}^{\cdot \text{s}^{-1}}$ (mean ± SD). During each measurement, participants were instructed to relax the musculature of the involved limb. This was verified by visual inspection of electromyographic (EMG) activition of m. biceps femoris and m. vastus lateralis via a computer monitor. ATFD was calculated as the mean of three intra-trial replicates of the net displacement of the patella and tibial tuberosity transducers.

3.3.3.2. Maximal voluntary muscle activation (MVMA)

Following a series of sub-maximal warm-up muscle activations an auditory signal was delivered randomly within 1-4 seconds cuing the participant to flex or extend their knee as rapidly and forcefully as possible against the immovable restraint provided by the apparatus. Another auditory signal was then given to the participant after approximately 3 seconds of maximal voluntary muscle activation (MVMA) to cue muscular relaxation. Three trials were performed, each separated by a minimum of 10 seconds. Static peak force (PF) was recorded as the mean response of three intra-trial replicates in which the highest force was recorded in each trial. The rate of force development (RFD) was calculated for each intra-trial replicate as the average rate of force increase between 25% and 75% and reported as the mean response of the three replicates. Performance of KE and KF were assessed in a randomised order.

3.3.3.3. Single leg hop for distance

Single leg hop tests (HOP) are widely used by physiotherapists and have been found to provide a reliable assessment tool during ACL rehabilitation (r_I = 0.92 to 0.98; Hopper et al., 2002; Reid et al., 2007). Participants were required to start from a single leg stance on their assessed limb, before producing a hop for maximum distance with a controlled landing in a stable position. No restriction was placed on arm movement, in order to provide assistance with balance if required. Distance was measured in centimetres from the toe at the start position to the heel at the landing position. Following two to three practice attempts, participants performed three maximal efforts, with the mean of the inter-trial replicates subsequently used for analysis.

3.3.4. Self-perceived knee function

3.3.4.1. Performance profile (PP)

The PP technique has been employed in a clinical environment with ACL-reconstructed patients (Doyle et al., 1998; Gleeson et al., 2008a; Gleeson et al., 2008b), with a level of reliability established through coefficient of variation ranging from ±9.2% to ±13.3% (95% confidence intervals) (Gleeson et al., 2005). Participants considered the question "What, in your opinion, are the elements of your knee in need of rehabilitation or improvement to obtain full recovery?" In conjunction with the researcher and physiotherapist, participants then generated up to 10 individual 'constructs' that they perceived to be important markers of their knee function. The individual constructs were subsequently mapped onto a PP (example illustrated in Figure 3.2). Participants completed the PP by considering the question "How does your injured limb feel at the present time compared to your non-injured limb on each of the qualities you have listed?" Responses were recorded by shading an area of the PP corresponding to the scale ranging from "extremely different to non-injured limb" (1) to "the same as my non-injured limb" (10). The participant's perceived score was then calculated as a percentage of the optimal score (10) to provide the basis for analysis. Mean PP scores across all constructs were calculated to negate inter-individual differences.

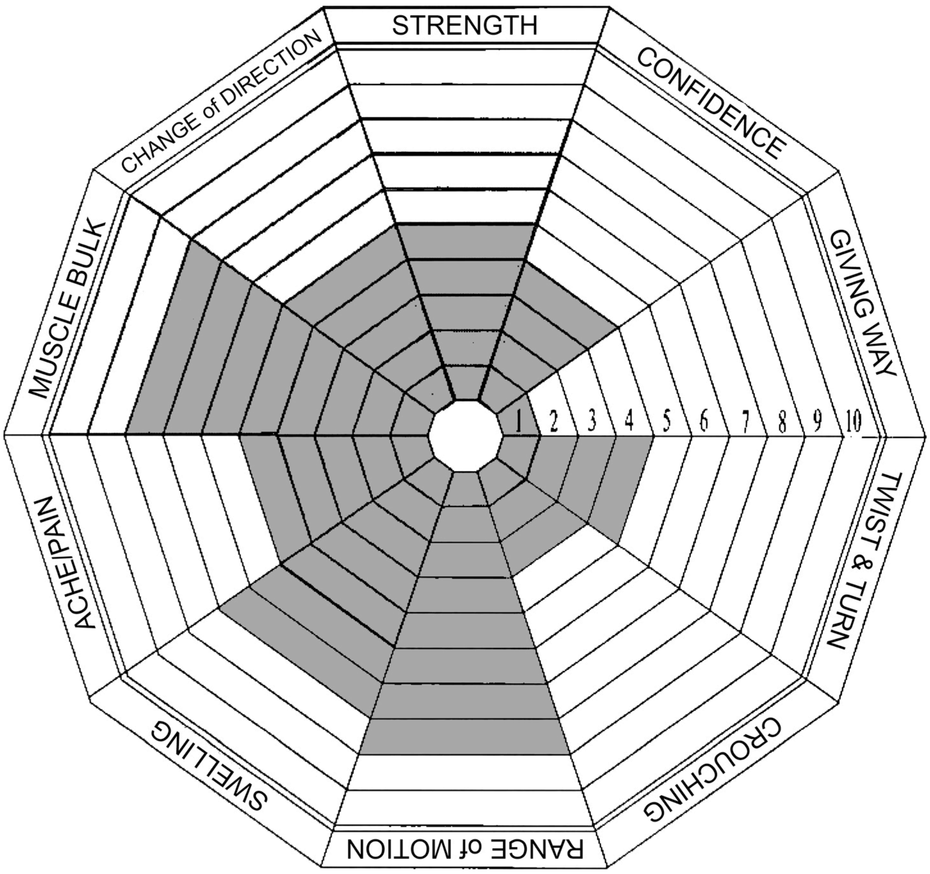

Figure 3.2 Example completed Performance Profile

3.3.4.2. International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form

The IKDC Subjective Knee Evaluation form is a short survey designed to allow the patient to subjectively evaluate their knee function over different categories ranging from daily living to sporting and recreational activities (an example form is provided in

Appendix A). In addition to several Likert-style questions on various aspects of knee function, the form contains questions that require the patient to state the highest level at which he/she could use his/her knee without exhibiting one of the key symptoms (for example pain, swelling, giving-way). Reliability of the IKDC survey has previously been reported as >0.87 (Higgins et al., 2007). Participants completed an IKDC form at each assessment session prior to musculoskeletal testing. IKDC scores were calculated as a percentage of the optimal score for subsequent analysis.

3.3.5. Statistical analysis

All statistical analyses were performed using PASW v18.0 (SPSS Inc. Chicago, Il, USA). The effect of reconstructive surgery and rehabilitation upon musculoskeletal performance (ATFD, PF, RFD and HOP) was assessed using separate two (limb: INJ; NON) by five (time: pre-surgery; 6 weeks; 12 weeks; 24 weeks; 48 weeks) fully repeated-measures ANOVAs. Changes in self-perceived knee function (IKDC and PP) during the surgical and rehabilitative process were analysed across the five assessment sessions using a single factor, repeated measures ANOVA. Greenhouse-Geisser corrections were applied where assumptions of sphericity were violated, as indicated by $_{GG}$. Post hoc analysis using paired sample t-tests were performed in order to confirm significant differences between limbs for specific time points, with an adjustment made via the Holm-Bonferroni procedure (Abdi, 2010) to protect against type 1 error.

Correlation coefficients (Spearman rank and Pearson product-moment) were calculated to explore relationships between self-perceived (IKDC and PP) and objective measures (ATFD, PF, RFD and HOP) for each of the five time-points. Musculoskeletal measures (ATFD, PF, RFD and HOP) for the injured limb were expressed as a percentage of the corresponding value for the non-injured limb in order to produce a limb symmetry index (LSI) (Thomee et al., 2011) based on a percentage scale of 100

([INJ/NON] x 100). PP and IKDC data was reported as a percentage of the maximal possible score. Relationships were also investigated to determine if improved knee-joint performance was only perceived subsequent to effectively 'testing' the new capabilities during functional activities, thus indicating a latency period before self-perceived measures would be able to reflect objective performance. As such, correlation coefficients were also calculated between musculoskeletal LSIs assessed at 6 weeks, 12 weeks and 24 weeks with IKDC and PP scores at 12 weeks, 24 weeks and 48 weeks, respectively. In addition, the percentage change between assessment sessions in terms of absolute performance measures was also determined, in order to ascertain whether any patterns of change were evident that were not detected by the other analyses. As such, correlation coefficients were calculated to establish if significant relationships were evident between the patterns of change for objective and perceived measures.

All data were analysed using standard descriptive statistics (mean ± SD), and statistical significance was accepted at $p<0.05$.

3.4. RESULTS

Patterns of change across the rehabilitation period are illustrated in Figures 3.3 to 3.9 (PP and IKDC, ATFD, KE-PF, KF-PF, KE-RFD, KE-RFD, and HOP, respectively). Group mean data for indices of self-perceived knee function and musculoskeletal performance are presented in Appendix B. The results of the one-way ANOVAs revealed significant main effects across time for both PP ($F_{[4,120]}=65.5$, $p<0.001$) and IKDC ($F_{[2.8,84.7\ GG]}=163$, $p<0.001$), demonstrating significant improvements in self-perceived knee function as the rehabilitation progresses. Repeated-measures ANOVAs revealed significant interactions between limb and time for ATFD ($F_{[1.3,38.1\ GG]}=550.5$, $p<0.001$), indicating a progressive decrease in knee laxity across time for the injured limb. Repeated-measures ANOVAs also revealed significant interactions between limb and time for KE PF ($F_{[1.3,38.9\ GG]}$ =56.8, $p<0.001$), KF PF ($F_{[1.2,36.7\ GG]}$ =24.2, $p<0.001$), KE RFD ($F_{[1.6,48.9\ GG]}$ =20.7, $p<0.001$), KF RFD ($F_{[1.8,54.7\ GG]}$ =22.1, $p<0.001$), and hop data ($F_{[2,60.9\ GG]}$ =38.3, $p<0.01$). These typically reflected a decrease in performance following surgery, accompanied by a progressive restoration of performance over time. The percentage changes in performance between time-points and associated effect sizes (ES) as calculated via Cohen's d ([$mean_1$ – $mean_2$] / SD) are presented for all self-reported and objective indices of performance in Table 3.1.

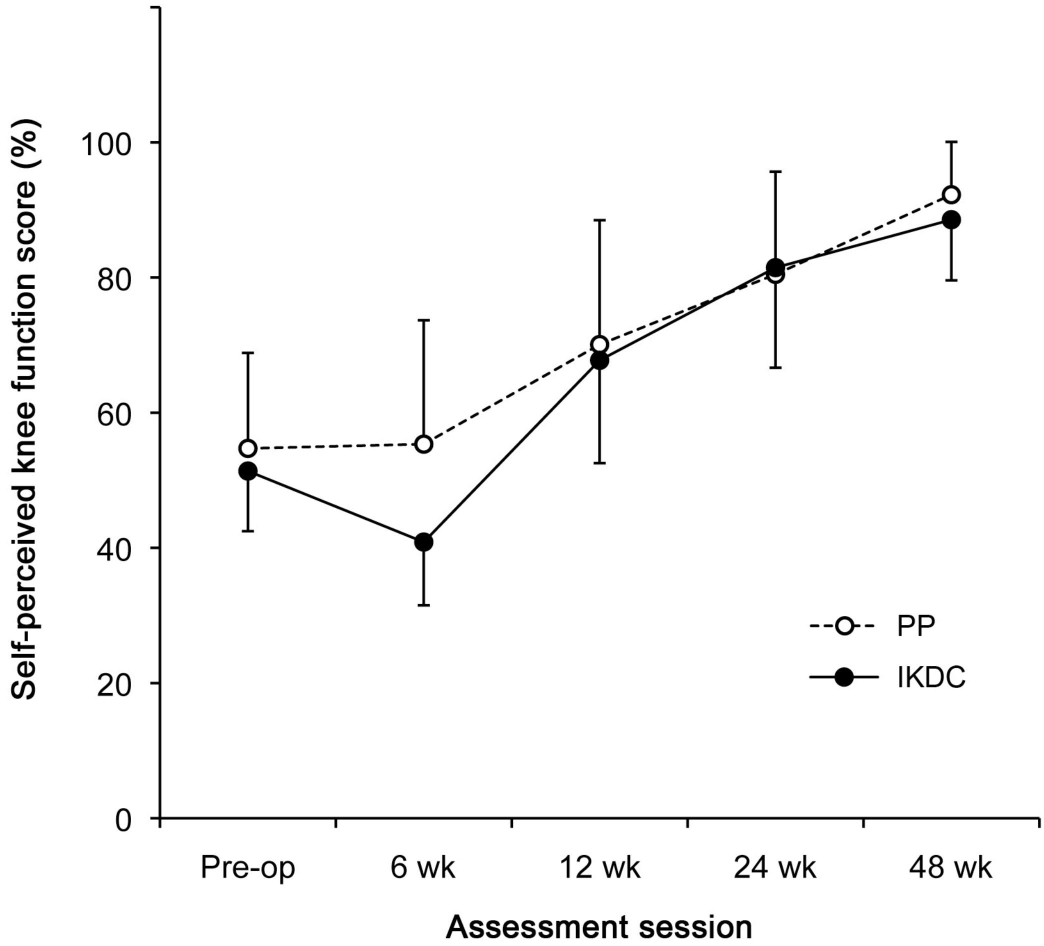

Figure 3.3 PP and IKDC responses across the rehabilitation period (group mean ± SD)

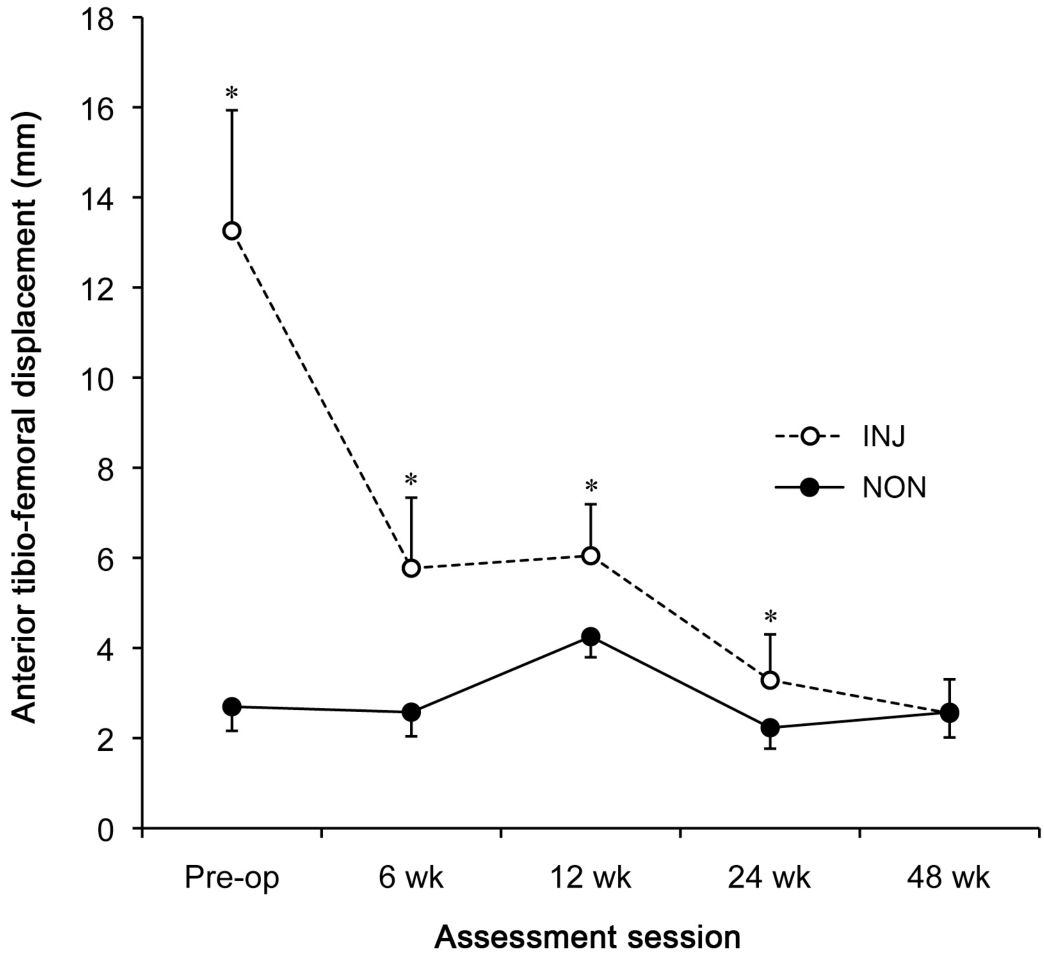

Figure 3.4 ACL laxity (as measured via anterior tibio-femoral displacement) across the rehabilitation period (group mean ± SD)
*Significant difference between INJ and NON ($p<0.001$)

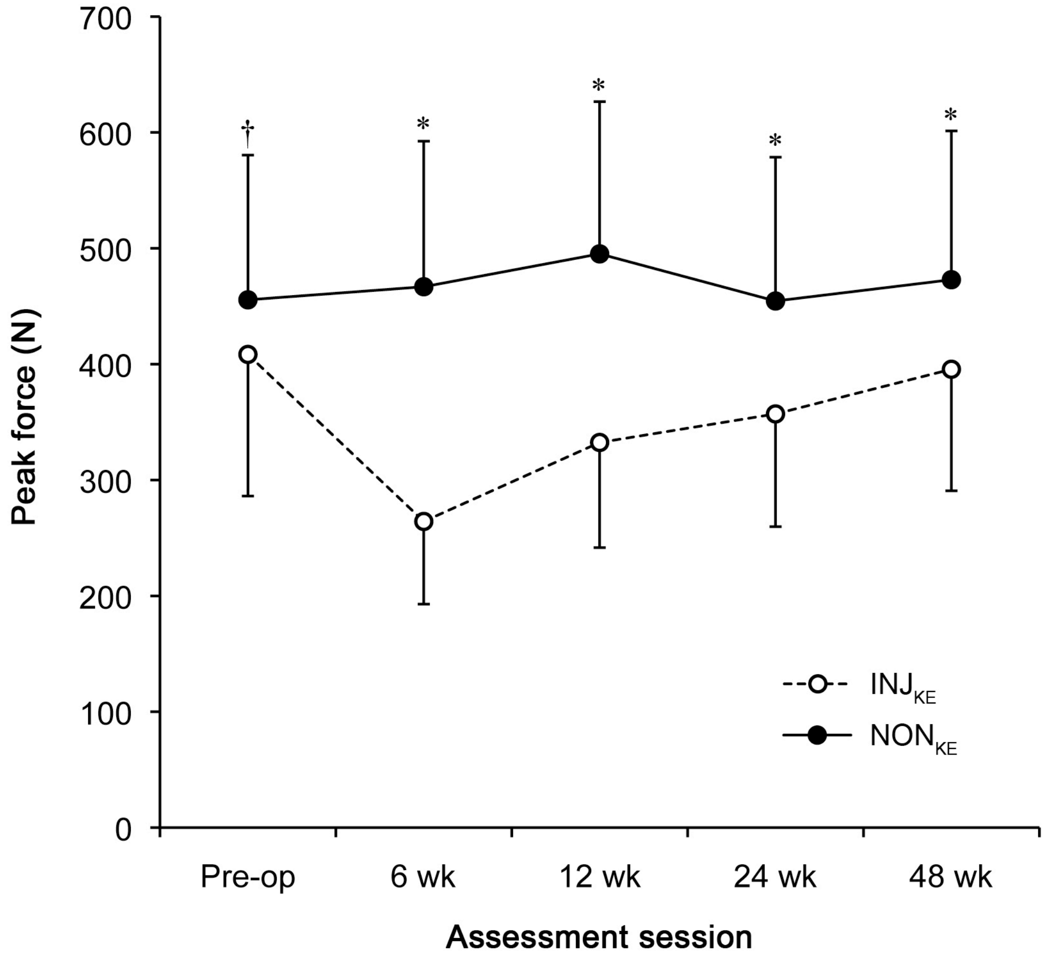

Figure 3.5 Knee extensor PF performance across the rehabilitation period (group mean ± SD)
*Significant difference between INJ and NON (p<0.001)

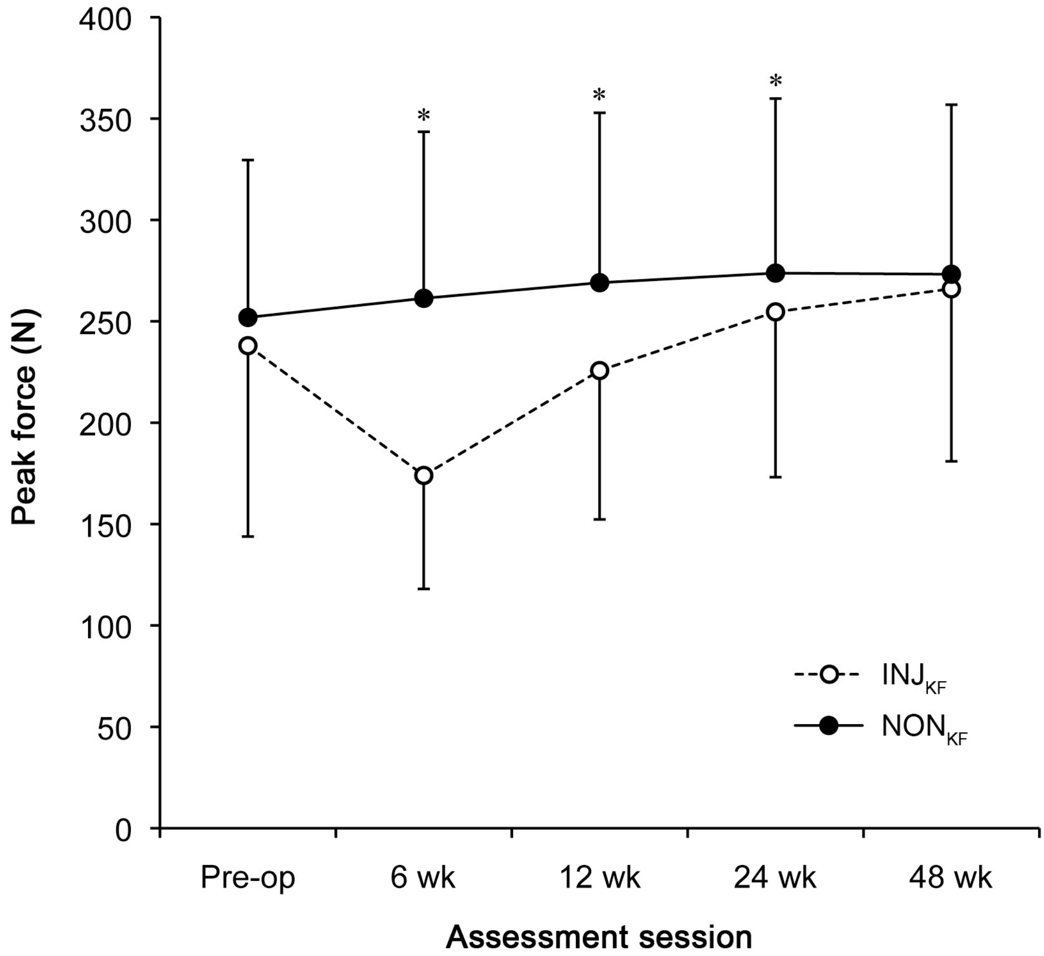

Figure 3.6 Knee flexor PF performance across the rehabilitation period (group mean ± SD)
*Significant difference between INJ and NON ($p<0.001$)

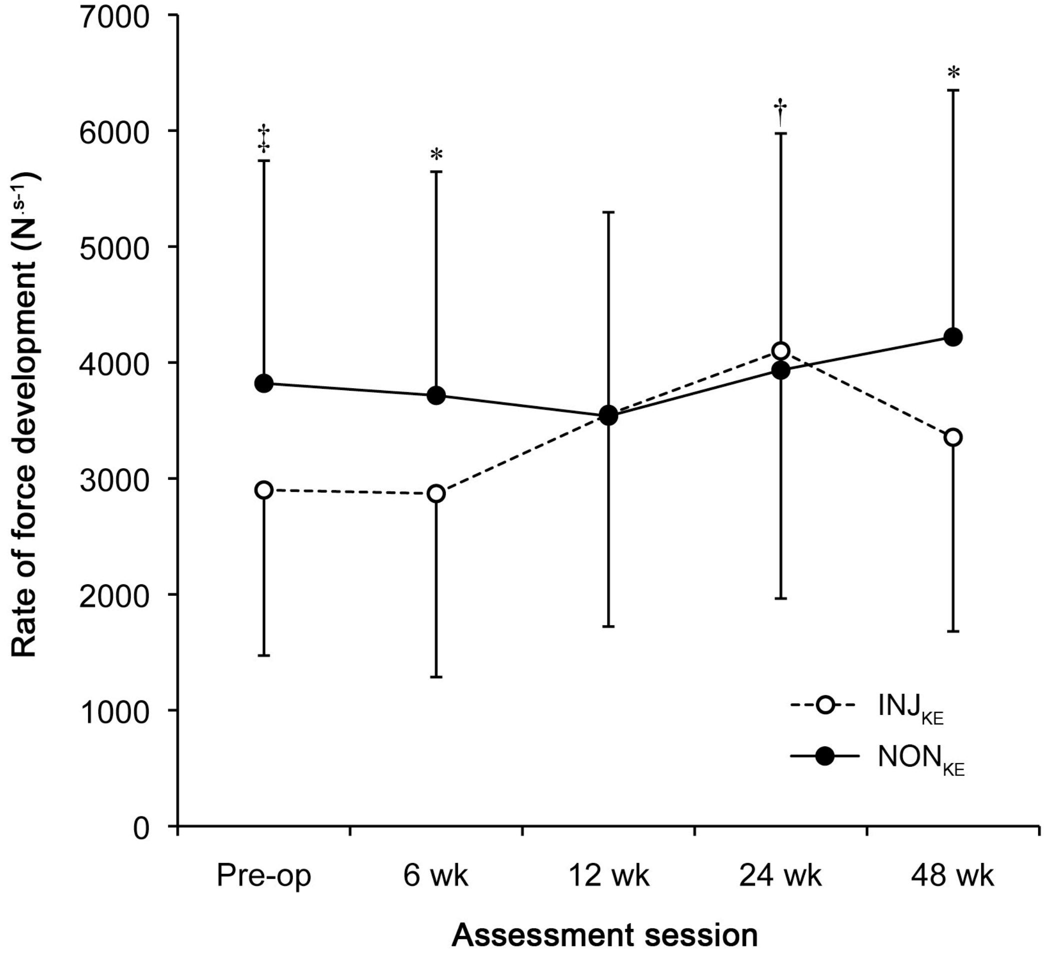

Figure 3.7 Knee extensor RFD performance across the rehabilitation period (group mean ± SD)
*Significant difference between INJ and NON ($p<0.001$)
‡ Significant difference between INJ and NON ($p<0.01$)
† Significant difference between INJ and NON ($p<0.05$)

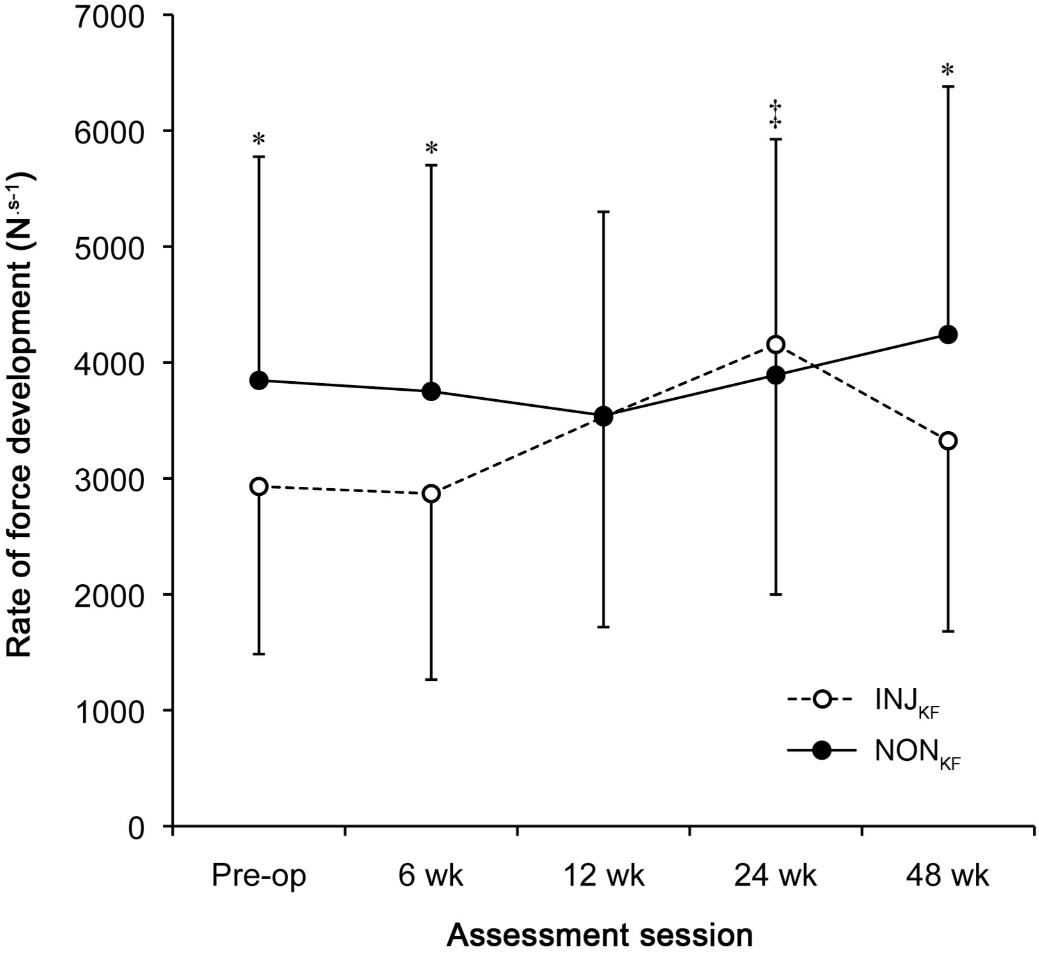

Figure 3.8 Knee flexor RFD performance across the rehabilitation period (group mean ± SD)
*Significant difference between INJ and NON (p<0.001)
‡ Significant difference between INJ and NON (p<0.01)

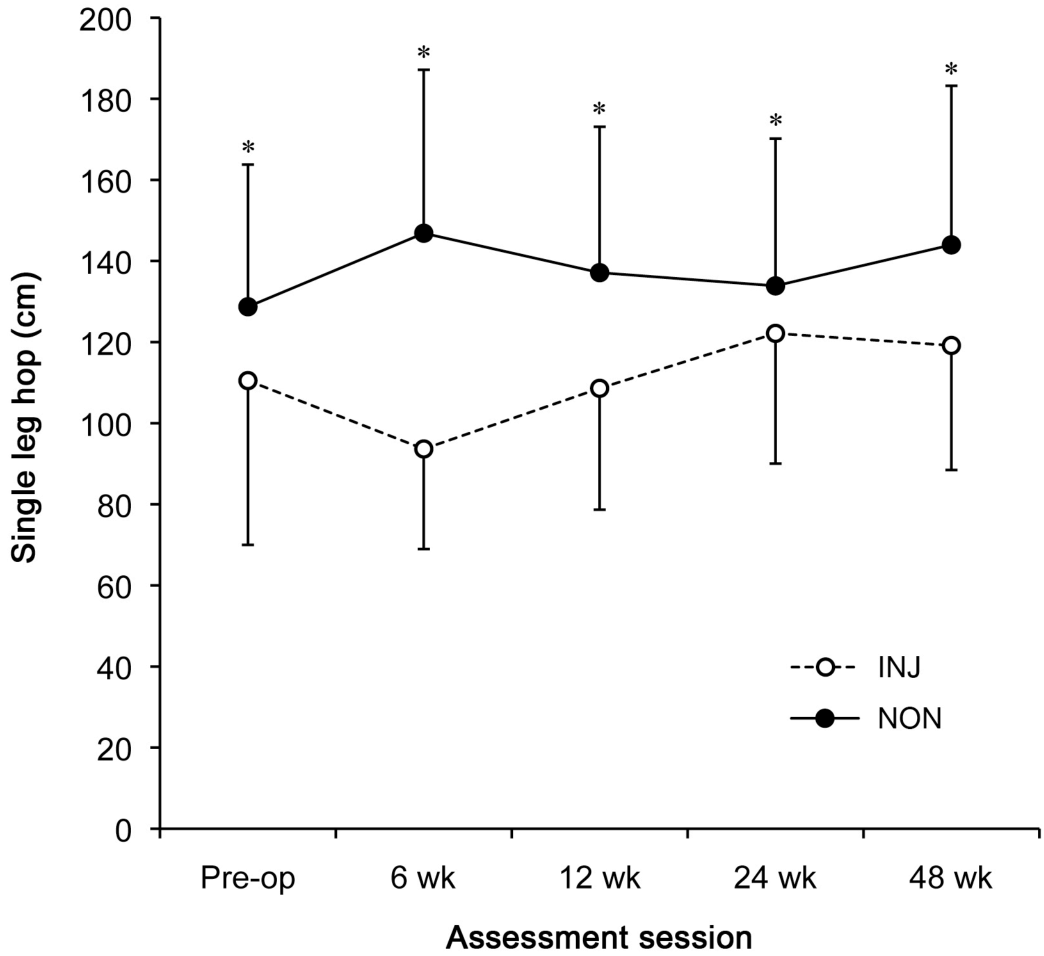

Figure 3.9 Single-leg hop performance across the rehabilitation period (group mean ± SD)
*Significant difference between INJ and NON (p<0.001)

Table 3.1 Percentage change (effect size) in self-perceived function and musculoskeletal performance between time-points during rehabilitation period

	Rehabilitation period			
Index	Pre-op to 6 weeks	6 to 12 weeks	12 to 24 weeks	24 to 48 weeks
PP	1.1 (0.0)	26.6 (0.7)*	14.8 (0.6)*	14.6 (0.9)*
IKDC	-20.5 (1.0)*	65.8 (1.5)*	20.2 (0.8)*	8.7 (0.6)†
ATFD				
INJ	-56.5 (1.7)*	4.8 (0.2)‡	-45.7 (1.6)*	-22.3 (0.8)*
NON	-4.5 (0.2)*	65.1 (1.7)*	-47.5 (1.8)*	15.4 (0.6)*
PF				
INJ_{KE}	-35.3 (1.2)*	25.8 (0.8)*	7.4 (0.3)*	10.8 (0.4)*
NON_{KE}	2.5 (0.1)*	6.1 (0.2)*	-8.2 (0.3)*	4.0 (0.1)*
INJ_{KF}	-26.9 (0.8)*	29.7 (0.7)*	12.8 (0.4)*	4.5 (0.1)*
NON_{KF}	3.7 (0.1)*	2.9 (0.1)*	1.8 (0.1)†	-0.2 (0.0)
RFD				
INJ_{KE}	-1.1 (0.0)	23.8 (0.4)*	15.4 (0.3)*	-18.2 (0.4)*
NON_{KE}	-2.7 (0.1)	-4.8 (0.1)‡	11.2 (0.2)*	7.3 (0.1)†
INJ_{KF}	-2.1 (0.0)	23.1 (0.4)*	17.7 (0.3)*	-20.0 (0.4)*
NON_{KF}	-2.5 (0.0)	-5.5 (0.1)‡	9.8 (0.2)*	9.0 (0.2)†
HOP				
INJ	-15.3 (0.5)*	16.0 (0.5)*	12.5 (0.4)†	-2.4 (0.1)‡
NON	14.1 (0.5)*	-6.6 (0.3)*	-2.4 (0.1)	7.5 (0.3)*

*Significantly different from previous assessment ($p<0.001$)
†Significantly different from previous assessment ($p<0.01$)
‡Significantly different from previous assessment ($p<0.05$)

Group mean LSI for each estimate of musculoskeletal performance are presented in Table 3.2. Correlation coefficients between musculoskeletal LSIs and PP and IKDC are presented in Table 3.3 and Table 3.4, respectively. The latent correlations between musculoskeletal LSIs and PP and IKDC are presented in Table 3.5 and Table 3.6, respectively. Correlations between percentage change in musculoskeletal performance and PP and IKDC are presented in Table 3.7 and Table 3.8, respectively.

Table 3.2 Limb symmetry indices (group means ± SD)

	Assessment Session				
Index	Pre-surgery	+6 weeks	+12 weeks	+24 weeks	+48 weeks
ATFD	494.8 ± 57.6	224.6 ± 38.1	142.0 ± 19.2	148.2 ± 34.1	98.9 ± 17.7
PF_{KE}	93.1 ± 34.2	56.6 ± 1.0	67.0 ± 1.9	78.7 ± 2.8	83.8 ± 2.4
PF_{KF}	96.1 ± 33.1	66.6 ± 4.3	83.7 ± 6.1	93.1 ± 6.9	97.2 ± 8.0
RFD_{KE}	83.7 ± 40.2	77.0 ± 7.1	100.2 ± 6.8	104.8 ± 9.0	80.5 ± 9.8
RFD_{KF}	84.0 ± 40.4	76.3 ± 7.8	99.4 ± 7.6	107.5 ± 10.1	79.7 ± 10.9
HOP	84.9 ± 19.3	64.1 ± 3.8	79.3 ± 5.2	91.6 ± 5.3	83.4 ± 6.2

Table 3.3 Limb symmetry index correlations with PP

	Assessment Session				
Index	Pre-surgery	+6 weeks	+12 weeks	+24 weeks	+48 weeks
ATFD	-0.12	0.07	0.16	0.13	0.00
PF_{KE}	0.33	0.26	0.22	0.18	-0.34
PF_{KF}	0.16	-0.22	-0.33	-0.11	-0.40‡
RFD_{KE}	0.29	-0.15	-0.10	-0.07	-0.33
RFD_{KF}	0.29	-0.06	-0.04	-0.08	-0.36
HOP	0.22	-0.14	-0.07	0.00	-0.41‡

‡Significant correlation ($p<0.05$)

Table 3.4 Limb symmetry index correlations with IKDC

	Assessment Session				
Index	Pre-surgery	+6 weeks	+12 weeks	+24 weeks	+48 weeks
ATFD	-0.25	-0.20	-0.27	-0.18	-0.15
PF_{KE}	-0.21	0.08	-0.20	-0.23	0.22
PF_{KF}	0.03	0.23	0.26	0.37‡	0.45‡
RFD_{KE}	0.10	0.24	0.13	0.20	0.57†
RFD_{KF}	0.10	0.24	0.12	0.17	0.56†
HOP	0.07	0.18	0.04	0.11	0.45‡

†Significant correlation ($p<0.01$)
‡Significant correlation ($p<0.05$)

Table 3.5 Limb symmetry index latent correlations with PP

Index	Assessment Session +6 weeks vs PP (+12 weeks)	+12 weeks vs PP (+24 weeks)	+24 weeks vs PP (+48 weeks)
ATFD	0.22	-0.02	-0.10
PF_{KE}	0.00	0.26	0.08
PF_{KF}	-0.36‡	-0.19	-0.31
RFD_{KE}	-0.19	0.04	-0.19
RFD_{KF}	-0.14	0.09	-0.15
HOP	0.08	-0.08	0.06

‡Significant correlation (p<0.05)

Table 3.6 Limb symmetry index latent correlations with IKDC

Index	Assessment Session +6 weeks vs IKDC (+12 weeks)	+12 weeks vs IKDC (+24 weeks)	+24 weeks vs IKDC (+48 weeks)
ATFD	-0.26	-0.26	-0.15
PF_{KE}	0.00	-0.22	-0.37‡
PF_{KF}	0.25	0.33	0.67†
RFD_{KE}	0.18	0.31	0.41‡
RFD_{KF}	0.16	0.26	0.34
HOP	0.07	-0.05	0.13

†Significant correlation (p<0.01)
‡Significant correlation (p<0.05)

Table 3.7 Correlations between percentage change in PP and musculoskeletal performance between time-points during rehabilitation period

Index	Assessment Session Pre-surgery to +6 weeks	+6 weeks to +12 weeks	+12 weeks to +24 weeks	+24 weeks to +48 weeks
ATFD	-0.14	-0.05	-0.03	0.18
PF_{KE}	-0.20	0.36‡	-0.25	0.32
PF_{KF}	-0.45‡	-0.11	-0.10	0.32
RFD_{KE}	0.03	-0.02	-0.17	0.36‡
RFD_{KF}	0.02	-0.04	-0.17	0.36‡
HOP	-0.03	-0.25	-0.02	0.37‡

‡Significant correlation (p<0.05)

Table 3.8 Correlations between percentage change in IKDC and musculoskeletal performance between time-points during rehabilitation period

Index	Assessment Session			
	Pre-surgery to +6 weeks	+6 weeks to +12 weeks	+12 weeks to +24 weeks	+24 weeks to +48 weeks
ATFD	0.10	0.01	0.13	-0.18
PF_{KE}	-0.24	0.09	-0.21	0.16
PF_{KF}	-0.35	0.09	-0.10	0.17
RFD_{KE}	0.09	0.13	-0.09	0.23
RFD_{KF}	0.09	0.12	-0.08	0.23
HOP	0.08	0.05	0.11	0.12

3.5. DISCUSSION

The aim of this study was to compare self-perceived measures of knee function with indices of musculoskeletal performance in order to identify stages of the ACL rehabilitation process where there is the greatest disparity between perceived and objective measures. Significant and anticipated changes to musculoskeletal performance were evident following surgery. Knee laxity was significantly reduced, as measured by a 56.5% improvement in ATFD from pre-surgery to 6 weeks, reflective of the new restraint in the form of the replacement graft. Furthermore, impairments to KE PF (35.3%), KF PF (26.9%) and HOP performance (15.3%) were apparent at 6 weeks post-surgery. Although RFD performance was minimally affected following surgery, the corresponding baseline values were substantially lower than the equivalent values for the non-injured limb (as indicated by the sub-optimal limb symmetry indices in Table 3.3). Following these initial impairments, ATFD, PF and HOP displayed gradual improvements across the rehabilitation phase. RFD performance followed a slightly different pattern, with increases in performance from week 6 to week 24, followed by an unanticipated reduction at 48 weeks. A caveat for the interpretation of RFD results is evidence of typically greater intra-session variability in test-retest conditions when compared to other indices of neuromuscular performance (~27%; Minshull et al., 2009).

This may provide some explanation as to the differing patterns of RFD performance across the rehabilitation period. Whilst some fluctuations in performance were evident for the non-injured limb across the rehabilitation period, these were typically small effect sizes (<0.4).

Although a lack of significant correlations were evident throughout the majority of the rehabilitation period, an increase in the strength of the relationship between IKDC and various indices of neuromuscular performance (PF_{KF}, RFD_{KE}, RFD_{KF}, HOP) became evident at 48 weeks. These findings highlight a discrepancy between self-reported and objective measures during the early to intermediate stages of rehabilitation (pre-surgery to 24 weeks). A lower self-perceived level of function in relation to musculoskeletal capabilities may represent a lack of confidence in the knee, and thus prompt a more cautious approach to rehabilitation. Conversely, if self-perceived function overestimates the current performance of the knee, then an overly aggressive strategy may be adopted. This issue is of particular concern during early stages of recovery (6 to 12 weeks), as the replacement graft is undergoing a process of ligamentisation and is in a weakened state due to a lack of vascularisation (Tohyama et al., 2009). This weakening of the graft contrasts with the progressive increases in dynamic exercise that characterise the accompanying phase of the rehabilitation programme (van Grinsven et al., 2010). A mismatch between perceived and actual capabilities at this stage may result in an inappropriately aggressive pacing strategy, which may in turn compromise the integrity of the graft (Marumo et al., 2005).

The objective assessments included in this current study were selected to encompass a range of important indicators of knee function, including integrity of the replacement graft, capacity for force generation, and dynamic stability. Changes in these various aspects of knee joint performance should theoretically impact upon functional tasks. As such, it could be expected that improvements in musculoskeletal function would be reflected by a concomitant increase in PP and IKDC ratings. However, the relationships between objective LSIs and PP would suggest otherwise (Table 3.3). These current findings contrast with those observed by Gleeson et al. (2008b), who reported significant positive relationships between PP and ATFD (r values of 0.68, 0.72 and 0.70 at pre-surgery, 8 weeks post and 10 weeks post, respectively), and between PP and PF (r values of 0.85 and 0.82 at pre-surgery and 8 weeks post, respectively). However, in a separate study, Gleeson et al. (2008a) identified a potential latency period before self-perceived knee function correlated with musculoskeletal performance, whereby changes in objective performance capabilities in ACL-reconstructed individuals are only perceived after being 'tested' during functional tasks. In this instance, PP correlated with ATFD (r = 0.68) and RFD (r = 0.65) only after a two-week latency period (PP scores from 10 weeks post correlated with ATFD and RFD at 8 weeks post). These findings were not mirrored in the results from the current study, as a low negative correlation between KF PF at week 6 and PP at week 12 was the only result of any significance. This may have been due to the longer duration between assessment sessions (≥ 6 weeks) that was perhaps too great to reveal a latency effect, as levels of performance will have made greater improvements across this period and thus not be detected. A possible explanation for the different findings reported by the two previous studies utilising PP (Gleeson et al., 2008a; Gleeson et al., 2008b) is the slight change in focus of the inventory. Whereas one investigation required the patients to focus on the qualities they perceived to be important for the optimal functioning of their knee (Gleeson et al., 2008a), the other placed greater emphasis on psychological aspects by specifically focusing on the emotions experienced by each patient since being injured (Gleeson et al., 2008b). The only notable correlations between PP and musculoskeletal performance were evident when examining percentage change scores, with significant positive correlations observed with KE PF (r = 0.36) for the period between week 6 and week 12, and also with KE RFD (r = 0.36), KF RFD (r = 0.36) and HOP (r = 0.37) between week 24 and week 48.

The relationships between IKDC and musculoskeletal performance follow a slightly different pattern to those exhibited by PP. A lack of strong correlations were evident at the early to intermediate stages (pre-surgery to 24 weeks) that were in agreement with results observed by Gleeson et al. (2008b). However, significant positive correlations were evident at 48 weeks with KF PF (r = 0.45), KE RFD (r = 0.57), KF RFD r = 0.56) and HOP (r = 0.45). In addition, significant positive correlations were observed between IKDC at week 48 and KF PF (r = 0.67) and KE RFD (r = 0.41) at week 24. The observation of an increasing strength of relationship between self-perceived and objective measures towards the latter stages of the rehabilitation period may be congruent with the concept of a learning effect, whereby patients have had time to become accustomed to the various sensations arising from their reconstructed knee after testing the joint during functional activities. This premise is consistent with the CGM theory of exercise regulation that postulates that selected RPE is matched to a 'template RPE' against which the anticipated task demands can be compared (Tucker, 2009). In the context of ACL rehabilitation, the patient exhibits insufficient experience of the sensations arising from the reconstructed limb, and is therefore unable to generate an accurate 'template'. As such, the lack of strong correlations for the majority of the rehabilitation period questions the capacity of self-perceived knee function to accurately reflect functional performance capabilities. This might have associated implications for the self-regulation of discrete rehabilitative exercise tasks, as described previously. It is not possible to determine if the current findings are due to a misperception of functional capabilities, or due to a lack of utility of the measurement scales. The PP technique enables patients to personalise the scale by generating individual 'constructs' that they deem to be important indicators of knee function, and has previously been deployed in a clinical environment (Doyle et al., 1998; Gleeson et al., 2008a; Gleeson et al., 2008b). In addition, the IKDC inventory was selected as a measure of self-perceived knee function because of its widespread usage in a clinical environment (Harreld et al., 2006; Higgins et al., 2007; Ardern et al., 2011b), and due to its previous application in conjunction with PP (Gleeson et al., 2008a; Gleeson et al., 2008b), as this would enable a comparison with previous research. Given that neither scale offered sufficient utility in terms of providing an indication of objective knee function during the early to intermediate stages of rehabilitation (pre-surgery to 24 weeks post-surgery), other self-reported measures of knee function, such as the Cincinnati Knee Rating System (Borsa et al., 1998), Lysholm Knee Rating System (Marx et al., 2001) or Knee Injury and Osteoarthritis Outcome Score (Thomee et al., 2007), might have provided a more accurate reflection of objective capability throughout the recovery process. However, whilst self-reported measures of knee function are widely used in a rehabilitation setting (Adams et al., 2012), their relevance has previously been questioned (Zarins, 2005; Gleeson et al., 2008a). An alternative consideration is that the indices of musculoskeletal performance selected for assessment possibly lack suitability. However, as previously highlighted, the selected measures represent a range of important indicators of objective knee function, and similar assessments are widely used to monitor the progress of ACL rehabilitation (Barber-Westin and Noyes, 2011). Moreover, the single-leg hop test is arguably a physical manifestation of self-perceived capabilities, whereby performance is likely to be highly determined by the patient's level of confidence in their knee. A lack of confidence or perception of poor knee function might plausibly prompt a smaller hop distance. As such, it could have been anticipated that this index of performance would have shared a stronger relationship.

RPE is derived from the integration of numerous sensations (Hampson et al., 2001). The dominant sensations that mediate the RPE response may vary depending on the mode and intensity of the exercise (Noble and Robertson, 1996). Similarly, self-perceived knee function will also be a product of multiple afferent signals and corollary discharges arising as a consequence of ACL-reconstructive surgery. Contributing factors may include pain and swelling, instability, limited range of motion, and impaired muscular strength and power. In this scenario, the most influential mediators may depend not only on the mode and intensity of exercise, but also on the phase of rehabilitation. For example, exercise during the early stages of rehabilitation focuses primarily on restoring muscle function whilst operating through a limited range of movement (Bailey et al., 2003; Kvist, 2004). This stage of recovery is distinguished by the biggest improvement in knee laxity (a reduction of 56.5% from pre-surgery to 6 weeks). However, the restrictive nature of the exercise tasks is important to place minimal stress on the replacement graft as it strengthens during the revascularisation process (Grodski and Marks, 2008), and consequently the dominant factors contributing to self-perceived knee function may be centred around sensations of pain, swelling and muscle weakness, as opposed to stability of the knee joint. For instance, stimulation of nociceptors may also have an inhibitory effect upon force generating capabilities (Rice and McNair, 2010), and an elevated pain response may supercede perceptual cues from other mechanoreceptors within the knee joint. As more dynamic exercise such as running and plyometrics is typically re-introduced between weeks 9 and 16 post-surgery (van Grinsven et al., 2010), an increased demand is placed upon the dynamic restraints to protect the joint, necessitating greater rapidity of force generation and coordination of muscle recruitment patterns (Alentorn-Geli et al., 2009). By these latter stages of rehabilitation, symptoms of pain and swelling have typically subsided (Cappellino al., 2012), and the dynamic nature of the exercise may stimulate increased self-awareness of the performance of the surrounding musculature. This may provide some explanation as to the relationships observed between IKDC and PF_{KF}, RFD, and HOP performance at 48 weeks.

3.6. CONCLUSION

The current findings reveal a lack of significant relationships between self-perceived and objective measures of musculoskeletal performance during the early to intermediate stages (pre-surgery to 24 weeks) of post-operative ACL rehabilitation. This disparity between self-perceived and actual function may reflect a lack of efficacy of the self-reported inventories, or possibly a misplaced level of confidence in the capabilities of the reconstructed knee. Considering the suggestion that a performer's level of self-efficacy regarding an exercise task could impact upon their RPE, it is plausible that the mismatch between perceived and actual capabilities might prompt the generation of an inaccurate RPE and consequently have implications for exercise regulation during discrete rehabilitative activities. It would be, therefore, of interest to explore if the previously reported linear relationship between RPE and exercise duration (as detailed in Chapter 2.5) is affected by the combination of injury and surgery during early to intermediate phases of ACL rehabilitation. This will help to ascertain whether or not patients are able to utilise RPE and their self-perceived exercise capabilities to help regulate their work-rate and accelerate their return to full activity. Before this can be investigated in a clinical setting, it is necessary to first test these principles in an asymptomatic population during an exercise mode that relates to rehabilitative activities. The use of a healthy population would enable greater experimental control whilst minimise inter-individual variations in performance. The first stage of this process involves determining the appropriate perceptual measurement tools and establishing the level of reliability and reproducibility of the selected inventories.

Chapter 4:
Reproducibility and reliability of two perceptual scales during an intermittent isometric fatigue task

CHAPTER 4: REPRODUCIBILITY AND RELIABILITY OF TWO PERCEPTUAL SCALES DURING AN INTERMITTENT ISOMETRIC FATIGUE TASK

4.1. ABSTRACT

The aim of this chapter was to assess the reliability of two perceptual measurement scales during a novel intermittent isometric fatigue task (IIF): i) measurement of perceived exertion using the category-ratio RPE scale (CR-10); ii) measurement of perceived percentage of completed task duration (PTD) using a visual analog scale. Eight recreationally active males were required to attend two assessment sessions, each of which required the participants to perform an entire IIF task at 60% baseline peak force (PF), through to termination. Measures of perceived exertion (CR-10) and perceived task duration (PTD) were recorded at 10% intervals across the relative duration of each IIF task. Inter-day reliability and variability of the CR-10 and PTD scales were established via calculation of intra-class correlation coefficients (ICC) and coefficient of variation (V%), respectively. Composite inter-day ICC scores were 0.82 ($p < 0.001$) and 0.85 ($p < 0.001$) for PTD and CR-10, respectively, suggesting a good level of agreement between trials for both PTD and CR-10. Composite V% values were 21.3 ± 15.4% and 22.7 ± 10.0% for PTD and CR-10, respectively, indicating greater intra-individual variability than reported in previous studies. Moreover, an intra-individual variability in CR-10 response of 33.1% was observed at 10% completed IIF duration, equating to 0.9 absolute units of measurement on a CR-10 scale. In order to reflect any variation in work intensity in the early stages of an IIF, CR-10 responses would, therefore, have to exceed this magnitude of 0.9 units.

4.2. INTRODUCTION

The findings in Chapter 3 identified a disparity between self-perceived and objective measures of knee function during the early to intermediate stages (pre-surgery to 24 weeks) of post-operative ACL rehabilitation. Given that self-efficacy of exercise performance has been shown to influence RPE (Hu et al., 2007), misplaced expectations concerning perception of knee function might plausibly have an associated impact upon the relationship between RPE and exercise task duration (TD). Various researchers have reported linear relationships between RPE and TD in cycling (Noakes, 2004; Eston et al., 2007; Crewe et al., 2008), running (Faulkner et al., 2008) and jumping activities (Pereira et al., 2011), suggesting a utility for RPE to act as a predictor of TD (Horstman et al., 1979; Eston et al., 2007). The potential practical benefit of this linear relationship is the application of RPE as a method of helping individuals regulate their pacing strategy to help produce an optimal performance. However, the relationship between RPE and TD is yet to be confirmed in intermittent isolated muscle activities that may have application to resistance training and rehabilitative exercise. Furthermore, with a variety of perceptual measurement scales having been utilised by the previous research (for an overview of methodologies, see Table 2.2), it is important to identify scales that may provide the greatest utility and reliability for measuring self-perceived capabilities during intermittent isolated muscle exercise.

Previous research investigating RPE in relation to TD have used measurement methods including both the Borg 15-point scale (Noakes, 2004; Eston et al., Crewe et al., 2008; Faulkner et al., 2008; Davies et al., 2009; Pereira et al., 2011) and the CR-10 scale (Albertus et al., 2005; Joseph et al., 2008; Swart et al., 2009). Whereas the 15-point Borg scale was designed to increase linearly with heart rate and exercise intensity (Borg, 1990), the CR-10 scale was developed to reflect the positively accelerating increase in lactate production associated with increasing exercise intensity (Noble et al., 1983). Thus, the CR-10 scale has been recommended in preference to the 15-point Borg scale for use in exercise that produces sensations of exertion and discomfort in a specific muscle group or area of the body (Borg and Kaijser, 2006; Buckley and Eston, 2007). Accordingly, the CR-10 scale has been deployed as a method of monitoring RPE in a variety of muscle-specific tasks, including grip strength (Demura and Yamaji 2009), trunk strength (Gruther et al., 2009), isolated knee extension and flexion (Pincivero et al., 2000; Pincivero et al., 2003a; Pincivero et al., 2003b), and also during cycling (Romer et al., 2002), walking (Chiu and Wang, 2007) and soccer training (Casamichana and Castellano 2010). Pincivero et al. (2000) reported a linear increase in CR-10 values in response to 10% incremental increases in intensity during isometric knee extensions. Participants were required to perform isometric activations at intensities ranging from 10% to 90% PF in a randomised order, and assign a CR-10 rating to each activation. The resulting group mean CR-10 responses at each work intensity were significantly different from those responses at the subsequent intensity, suggesting that the scale demonstrated sufficient measurement sensitivity to detect 10% variations in force. This led the authors to recommend the CR-10 scale in a prescriptive capacity as a method of regulating workload in resistance exercise. In the context of pacing, CR-10 responses have also been reported to demonstrate a linear increase during cycling exercise when plotted as a proportion of the completed exercise duration (Albertus et al., 2005; Joseph et al., 2008).

Test-retest reproducibility and reliability of the CR-10 scale has previously been investigated, yielding a coefficient of variation (V%) ranging from 14.5% to 17% (Elfving et al., 1999; Day et al., 2004) and intra-class correlation coefficients (ICC) of 0.84 to 0.95 (Elfving et al., 1999; Day et al., 2004; McGuigan et al., 2004). However, it has been acknowledged that the capability of the CR-10 scale to reflect changes in exercise intensity may differ under varying levels of fatigue (Pincivero et al., 2000). It is therefore important to establish the level of precision afforded by the CR-10 during acute fatigue, in order to understand the implications for using the scale to predict TD and help to regulate exercise performance.

RPE scales are designed for a performer to rate the sensations of effort and discomfort experienced when performing a given exercise task (Noble and Robertson, 1996). However, Swart et al. (2012) have recently provided evidence that the perception of effort can be isolated from the sensations of pain and discomfort arising from exercise, by utilising separate scales to distinguish between exertion and effort during 100km cycling trials that included 5 maximal sprints performed at pre-determined intervals across the duration of the task. The resulting findings demonstrated high levels of perceived effort following each maximal sprint, whilst perceived exertion was shown to increase as the time-trial progressed. This distinction highlights the capability to perform maximal efforts in the absence of severe symptoms of exertion, and also that it is possible to summon an increased effort whilst in a pre-existing state of severe exertion, such as an end-spurt in the latter stages of a race (Abbiss and Pfeiffer, 2010). In accordance with this principle, it is plausible that performers could generate a high RPE, yet simultaneously perceive that they are capable of continuing the exercise bout for a sustained period. In this regard, a direct prediction of a performer's self-perceived time-to-exhaustion over the course of an exercise bout might plausibly produce a different response in comparison to RPE. It is, therefore, of interest to explore whether or not a direct prediction of exhaustion time would share a stronger relationship with TD than RPE. This concept has previously been investigated with the design of an estimated time limit (ETL) scale that requires the performer to make a conscious prediction of time remaining in an endurance exercise task (Garcin et al., 1999; Garcin et al., 2004). The ETL scale requires performers to consider the question "how long would you be able to perform an exercise at this intensity up to exhaustion?" and requires them to provide a response on a 1-20 scale with accompanying descriptors ranging from "more than 16 hours" to "2 minutes". Although the ETL scale attempts to address the issue of obtaining a direct prediction of remaining TD, there is insufficient evidence to support its utility in isolated muscle exercise. Firstly, the timescale incorporated within the ETL is inappropriate for a shorter bout of intermittent isolated muscle activity that may be performed during a discrete rehabilitation session. In addition, although reliability of the ETL has been provided via Pearson correlations ranging from 0.74 to 1 (Coquart and Garcin, 2007), it has been argued that correlation coefficients merely provide a measure of association as opposed to an estimate of the size of within-subjects variability (Lamb et al., 1999). Moreover, the construct validity of this scale is questionable, with ETL responses obtained at 2 and 4 minutes into a cycling task demonstrating a lack of accuracy in predicting TD (Garcin et al., 2004). It is apparent that the ETL scale would have limited application to shorter duration intermittent and isolated muscle activity that is reflective of resistance or rehabilitative exercise. However, this does not discount the potential merits of obtaining conscious predictions of TD with regard to regulating exercise performance. Indeed, if an appropriate scale is found to share a relationship with TD, then this could provide substantial benefits in regulating exercise performance in both resistance training and clinical settings.

The aim of this chapter is to assess the reliability of two perceptual measurement scales during a novel intermittent isometric fatigue task (IIF): i) measurement of RPE using the CR-10 scale; ii) measurement of perceived percentage of completed task duration (PTD) using a visual analog scale.

4.3. METHODS

4.3.1. Participants

Eight recreationally active males (age 24.1 ± 4.1 years; height 179.6 ± 7.5cm; body mass 89.3 ± 11.6kg) provided written informed consent to participate in the study. All participants were asymptomatic of injury and were instructed to abstain from strenuous physical activity for the 24 hours preceding each testing session. The sample size was reduced from an initial sample of 16, as some participants failed to complete the full testing schedule while others were omitted due to a lack of adherence to the activity restrictions. Assessment protocols were approved by the Nottingham Trent University Ethical Committee for Human Testing.

4.3.2. Experimental Procedures and Design

Participants were required to attend the laboratory on a total of three occasions, each separated by 48-72 hours. The first occasion involved familiarisation and accommodation to rapid maximum voluntary muscle activation (MVMA) of the quadriceps, and perceptual measures (described below). Also included was a brief exposure to an intermittent isometric fatigue task (IIF) for a total of 8 sets at an intensity of 60% baseline peak force (PF). Occasions two and three served as assessment sessions, each of which required the participants to perform an entire IIF task at 60% baseline PF, through to termination. Estimates of static volitional neuromuscular performance were obtained prior to each IIF.

Following a standardised warm-up of five minutes cycle ergometry performed at 90 W, and an additional five minutes of stretching of the involved musculature, participants were secured in a seated position on a custom built dynamometer (Minshull et al., 2011). The lever arm of the dynamometer was attached to the involved leg of the participant via a padded ankle cuff secured just proximal to the lateral malleolus and the lever arm was at an angle perpendicular to the tibia (Figure 4.1). The muscle action was localised through the use of adjustable strapping across the torso, pelvis and anterior thigh proximal to the knee joint. Throughout testing, the knee position was maintained at a functionally relevant angle of 25° (0.44 rad) which has been associated with the greatest mechanical strain on key ligaments (Li et al., 1999) and identified for each participant during activation of the involved musculature using a goniometry system. The hip angle was 60° (0° = full extension) and the non-involved limb rested on a padded surface in order to reduce leverage during activation of the musculature of the involved limb.

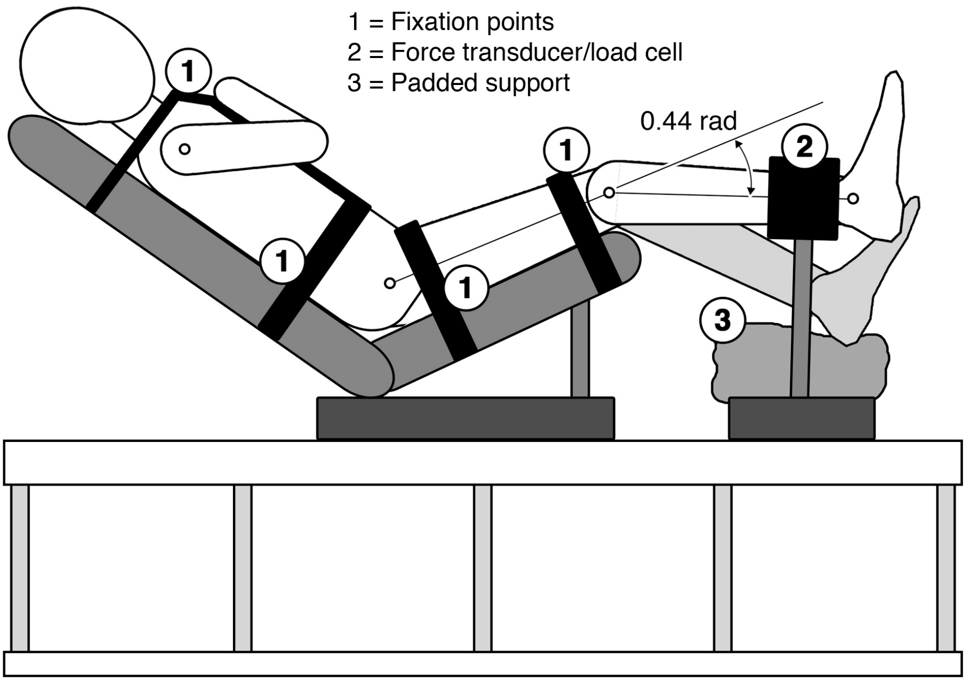

Figure 4.1. Participant and dynamometer orientation

4.3.3. Intermittent Isometric Fatigue task (IIF)

An IIF consisting of sets of ten sub-maximal muscle activations of the knee extensors was performed in time to an audible sound-track of bleeps that cued a work:rest ratio of 1s:1s. This work:rest ratio has previously been utilised in isometric knee extension and flexion (Gleeson et al., 2008) and isometric hand-grip tasks (Shoemaker et al., 1999). The participant was able to observe their efforts on a computer monitor to ensure their attainment of the target force (see Figure 4.2 for example data). After each set, a rest period of ten seconds enabled the participant to record their perceptual measures (described below). In order to minimise any influence of participants' previous scores on their current perception, blank recording sheets were provided after every set. Termination criterion for the IIF were defined by: the participant's inability to maintain target force for three consecutive efforts in any set; when the majority of the efforts within the set did not reach the target force, or; at the point of volitional exhaustion. All participants were verbally encouraged during periods of muscle activation.

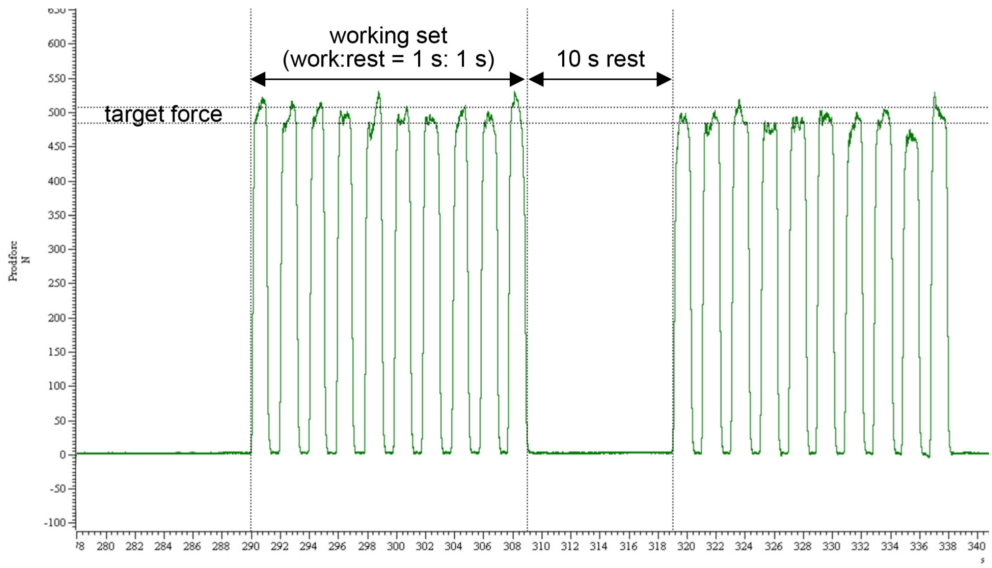

Figure 4.2. Example force trace illustrating IIF work:rest ratios

4.3.4. Perceptual measures

4.3.4.1. Perceived Exertion: CR-10 Scale

A modified version of the CR-10 scale was used to measure RPE (Borg, 1998). This version omitted the numerical ratings 0.3, 0.5, 1.5 and 2.5 (Lloyd et al., 1991; Allman and Rice, 2003; Pincivero et al., 2003a, Pincivero et al., 2003b; Day et al., 2004; McGuigan et al., 2004) and the verbal descriptors were modified from 'weak' and 'strong' to 'light' and 'hard', respectively (Pincivero et al., 2003a). In addition, the 'maximal' rating with the facility to select numbers above 10 was also omitted (Lloyd et al., 1991; Allman and Rice, 2003; Pincivero et al., 2003b; McGuigan et al., 2004; Yoon et al., 2007; Testa et al., 2012). These modifications were made following extensive pilot testing, in order to maximise participant understanding and improve application of the scale (modified scale illustrated in Figure 4.3). High and low reference anchors were applied to provide a context through which participants could evaluate their RPE and provide the scope to differentiate between work intensities (Noble and Robertson, 1996). The low anchor was applied during the passive recovery period prior to the pre-IIF MVMA, with participants instructed to "think about the feelings in your working muscles during this recovery period and to assign a rating of 0 to those feelings." The high anchor was applied immediately following each pre-IIF MVMA, by instructing the participants to "think about the feelings in your working muscles during the maximal effort and assign a rating of 10 to those feelings." This anchoring procedure has previously been employed in isometric fatigue tasks (Allman and Rice, 2003; McGuigan et al., 2004; Yoon et al., 2007). CR-10 responses were obtained during each inter-set rest period during the IIF. Participants were asked to consider the question "Think about the feelings in your working muscles during your last effort, and rate those feelings" (defined as the last repetition in the preceding set). Participants selected a response by circling the appropriate number from the scale, and were permitted to select fractional values if required. It was emphasised to participants that they should provide honest responses regarding their perceived exertion, as opposed to recording erroneous values to conform to perceived expectations.

0	-	nothing at all
1	-	very light
2	-	light
3	-	moderate
4	-	somewhat hard
5	-	hard
6		
7	-	very hard
8		
9		
10	-	extremely hard

Figure 4.3. Modified CR-10 scale (adapted from Pincivero et al., 2003b). Participants selected their rating in response to the statement "Think about the feelings in your working muscles during your last effort and rate those feelings."

4.3.4.2. Perceived percentage of completed task duration (PTD)

Visual analog scales (VAS) provide a very quick and simple method for a variety of functions such as measuring pain (Katz and Melzack, 1999) or self-efficacy (Turner et al., 2008). Test-retest reliability of VAS scales has previously been reported with ICC values ranging from 0.82 to 0.97 (Le Resche et al., 1988; Vieira et al., 2005; Shmueli et al., 2008). A VAS was selected for the estimation of PTD as this could be applied to all participants and mitigate against heterogeneity of task duration. Units of measurement were omitted from the VAS to as there is the suggestion that these additional elements can affect the distribution of responses (Huskisson 1983).

Measures of PTD were obtained using a VAS with ‘beginning’ and ‘end’ anchors placed at either end of a 100mm line (illustrated in Figure 4.4). The 100mm length scale has previously been recommended above other lengths (50 and 200mm) due to providing smaller measurement errors (Seymour et al., 1985). Participants considered the question “Based on your last set of efforts and brief recovery, how far from the end of the test do you think you are?” and marked the line with their response accordingly. Responses were measured with a ruler and converted into percentages for subsequent analysis.

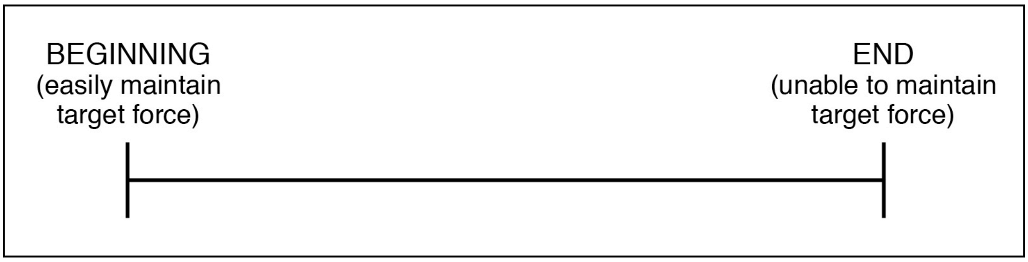

Figure 4.4. VAS scale

4.3.5. Assessment of neuromuscular performance

Following a series of sub-maximal warm-up muscle activations an auditory signal was delivered randomly within 1-4 seconds cuing the participant to extend their knee as rapidly and forcefully as possible against the immovable restraint provided by the apparatus. Another auditory signal was then given to the participant after approximately 3 seconds of maximal voluntary muscle activation (MVMA) to cue muscular relaxation. Three trials were performed, each separated by a minimum of 10 seconds. Static peak force (PF) was recorded as the mean response of three intra-trial replicates in which the highest force was recorded in each trial. Rate of force development (RFD) was calculated for each intra-trial replicate as the average rate of force increase between 25% and 75% and reported as the mean response of the three replicates.

4.3.6. Statistical analysis

All statistical analyses were performed using PASW v18.0 (SPSS Inc. Chicago, Il, USA). Perceptual measures were obtained at 10% intervals of the completed task duration (CTD), with CR-10 and PTD scores at 10% to 100% of the IIF task subsequently used for analysis. For those individuals whose scores did not fall on a 10% interval, a cubic spline function enabled interpolation of a value that was subsequently used for analysis (Keele, 2008).

Intra-class correlation coefficients (ICC) were calculated to establish reliability and provide an indication of the degree of association between inter-day measures (Bruton et al., 2000). ICCs were calculated for inter-day IIF duration, neuromuscular performance, and perceptual measures.

Coefficient of variation (V%) (SD/mean) across the inter-day trials was also calculated for each individual to establish the reproducibility of each measure, as this index provides an estimate of variability that is independent from the inter-subject heterogeneity (Mercer and Gleeson, 2002). A correction for V% for small sample bias was calculated according to the expression (SD/mean) × (1+[1/4n]) × 100 (Sokal and Rohlf, 1981). Outliers were detected at 95% significance using the Dixon Q-test (Rorabacher, 1991). Due to two participants exhibiting a learning effect not evident in the remainder of the sample, the decision was taken to Winsorise the relevant data, by replacing the errant data points with neighbouring values (Sokal and Rohlf, 1981). Winsorised PTD V% values were imputed for two participants across a combined total of six time points. A Winsorised CR-10 V% value was imputed for one participant at a single time point.

Paired samples t-tests were used to explore inter-day differences in IIF duration. IIF set values were log transformed (log 10) to satisfy assumptions of normality. Paired t-tests were also employed to establish significant differences between neuromuscular performance measures (PF, RFD, EMD_{VL}, EMD_{VM}), and between corresponding perceptual measures at equivalent time points at each 10% of relative TD.

All data were analysed using standard descriptive statistics (mean ± SD), and statistical significance was accepted at $p<0.05$.

4.4. RESULTS

Composite V% values (mean and SD calculated from the sum of the average V% values from each CTD time point) were 21.3 ± 15.4% and 22.7 ± 10.0% for PTD and CR-10, respectively. Composite ICC values (range comprising all CTD time points) were 0.82. Composite inter-day ICC scores (range comprising all CTD time points) were 0.82 ($p < 0.001$) and 0.85 ($p < 0.001$) for PTD and CR-10, respectively. Both PTD and CR-10 inter-day ICC scores exceeded an acceptable level of agreement of 0.80 (Currier, 1984). Group mean data (± SD) for PTD and CR-10 responses measured over the duration of the IIF1 and IIF2 trials, along with corresponding V% and ICC values are presented in Table 4.1 and Table 4.2, respectively. Group mean data for IIF duration and indices of neuromuscular performance, along with corresponding V% and ICC values are presented in Table 4.3. ICCs indicated high levels of agreement across the inter-day trials for all neuromuscular performance measures (ICC > 0.84; $p < 0.001$). Paired t-tests revealed no significant differences for IIF duration, neuromuscular performance measures, or perceptual measures between day 1 and day 2.

Table 4.1 CR-10 responses during IIF1 and IIF2 (group means ± SD), with corresponding V% and ICC

% of CTD	CR-10 IIF1	IIF2	V%	ICC
10	2.4 ± 1.4	3.1 ± 1.5	33.1 ± 27.0	0.84†
20	3.3 ± 1.7	4.4 ± 1.8	34.8 ± 27.3	0.53
30	4.5 ± 1.9	5.5 ± 1.8	29.0 ± 26.4	0.26
40	5.3 ± 2.3	6.8 ± 2.4	31.3 ± 37.8	0.42
50	6.8 ± 1.9	7.6 ± 1.9	19.2 ± 13.6	0.14
60	7.7 ± 1.5	8.4 ± 2.1	18.3 ± 19.9	0.31
70	8.6 ± 1.7	8.9 ± 1.9	20.0 ± 25.2	-2.14
80	9.3 ± 0.9	9.3 ± 1.5	11.9 ± 15.0	-0.80
90	9.9 ± 0.3	9.6 ± 0.9	3.0 ± 4.2	-0.29
100	10.0 ± 0.0	10.0 ± 0.0	n/a	n/a

†Significant ICC (p<0.01)

Table 4.2 PTD responses during IIF1 and IIF2 (group means ± SD), with corresponding V% and ICC

% of CTD	PTD IIF1	IIF2	V%	ICC
10	20.4 ± 11.7	30.4 ± 17.7	46.9 ± 30.9	0.11
20	33.1 ± 18.6	41.9 ± 22.2	34.3 ± 31.8	0.46
30	43.7 ± 23.4	50.8 ± 21.4	41.9 ± 31.2	0.08
40	53.7 ± 23.7	61.5 ± 20.1	24.2 ± 15.4	0.25
50	63.7 ± 24.9	69.0 ± 18.6	19.2 ± 12.5	0.35
60	74.6 ± 21.2	77.8 ± 15.6	14.7 ± 12.4	0.16
70	82.3 ± 23.8	83.4 ± 14.9	15.4 ± 10.2	-0.46
80	92.2 ± 7.9	89.2 ± 10.8	9.7 ± 8.9	-0.17
90	96.7 ± 6.2	92.4 ± 9.2	5.3 ± 4.9	-0.28
100	98.3 ± 2.6	95.5 ± 7.7	1.5 ± 1.6	0.02

Table 4.3 IIF duration and indices of neuromuscular performance for day 1 and day 2 (group means ± SD), with corresponding V% and ICC

Index		**Day 1**	**Day 2**	**V%**	**ICC**
IIF#	(sets)	22.5	30.1	36.8 ± 30.2	0.57
PF	(N)	660.7 ± 137.5	664.9 ± 146.7	4.9 ± 1.3	0.99*
RFD	($N^{.s-1}$)	3053 ± 912	3092 ± 1046	21.1 ± 7.2	0.94*
EMD_{VL}	(ms)	36.7 ± 12.6	31.4 ± 4.7	17.2 ± 9.8	0.84*
EMD_{VM}	(ms)	34.9 ± 7.3	33.6 ± 7.0	17.2 ± 5.7	0.85*

#IIF values reverse log transformed
*Significant ICC (p<0.001)

4.5. DISCUSSION

The results of the current study demonstrate that the composite V% and ICC values for the PTD and CR-10 scales possess similar overall levels of measurement reliability during performance of an IIF. The composite V% values for perceptual measures were slightly higher than previously reported values for CR-10 in isometric and isotonic resistance exercise (14.5% to 17%: Elfving et al., 1999; Day et al., 2004). When evaluated separately for each 10% increment in exercise duration, a greater relative intra-individual variability in perceptual responses were evident during the early stages of the IIF, as indicated by V% values (Tables 4.1 and 4.2). The smaller relative errors towards the end of the IIF may be due to a 'clamping' effect from the uppermost value of the respective scales. They may also reflect the participants' improvement in using the rating scales due to their learning through the feedback they obtained during the test. However, the inclusion of a separate familiarisation session within the current study was designed to accommodate and habituate the participants to the exercise task and procedures, and minimise learning effects between IIF1 and IIF2. An intra-individual variability in CR-10 response of 33.1% was observed at 10% CTD, equating to 0.9 absolute units of measurement on a CR-10 scale. In order to reflect any variation in work intensity in the early stages of an IIF, CR-10 responses would, therefore, have to exceed this magnitude of 0.9 units.

Composite ICC values were comparable to those previously reported for the CR-10 (0.84 to 0.95: Elfving et al., 1999; Day et al., 2004; McGuigan et al., 2004). However, when the data was explored for each separate 10% increment in exercise duration, the ICC relationships were noticeably weaker (Table 4.1 and Table 4.2 for CR-10 and PTD, respectively). It is possible that grouping subsets of data at discrete time points creates a more homogeneous sample by reducing the between-subjects variance, resulting in a weaker correlation (Bruton et al., 2000). These findings mirror those reported by Pincivero et al. (2003), who discovered relatively weak ICCs for CR-10 values (-0.50 to 0.46) that were obtained in response to a range of isometric muscle activations performed at intensities ranging from 10% through to 90% MVMA separated by 10% intervals. Other research has grouped CR-10 responses that were obtained after performing resistance exercise across a range of intensities (Day et al., 2004; McGuigan et al., 2004) or that were recorded at a range of time points throughout the duration of an isometric fatiguing muscle activation (Elfving et al., 1999). This approach provides a single ICC value, and creates a more heterogeneous sample and a higher level of reliability. It can be argued that grouping of data across the full spectrum of time points provides a clearer indication of the reliability of the perceptual responses, and is consistent with approaches adopted in previous research.

The IIF was selected because the static nature of the task mimics muscle exercise performed by an ACL-reconstructed population during the early stages of rehabilitation when dynamic exercise is restricted (Grodski and Marks, 2008). In addition, the isolated nature of the task removed the potential variable of differing levels of technical ability between participants, such as might be expected in the performance of a more complex multiple-joint exercise such as a free-weight squat. Extensive pilot testing was undertaken in order to devise a protocol that provoked a fatiguing response within a manageable timeframe that replicated the duration of a bout of intermittent resistance exercise, yet still afforded participants sufficient time to consider their perceptual responses during inter-set rest periods. The inclusion of a separate familiarisation session within the current study was designed to accommodate and habituate the participants to the exercise task and procedures, and minimise learning effects between IIF1 and IIF2. Pincivero et al. (2003) previously reported a low level of inter-day reliability in CR-10 response, that was attributed in part to a lack of habituation to the testing procedures, and significant difference in PF force values between assessment sessions. In the current study, the low variability of inter-day PF (4.9%) indicates that participants performed the IIF tasks at similar absolute target forces on each occasion. Moreover, the inclusion of a habituation procedure meant the proportion of error attributable to learning effects is likely to be comparably less than that reported in previous related research. Whilst there was no significant difference in duration between IIF1 and IIF2, the V% of 36.8 ± 30.2 indicates a substantial intra-individual variability with regard to performance of the IIF tasks. However, considerable intra-individual variability has also been previously reported in a more traditional constant load cycling test (V% = 21 to 26.6: Hill and Rowell, 1996; Jeukendrup et al., 1996).

The CR-10 scale was selected to provide a measure of RPE due to its application to localised muscle exercise (Noble et al., 1983; Pincivero et al., 2000). From the current research, it is impossible to determine whether the level of test-retest reliability (22.7%) of the CR-10 was solely due to an altered 'template RPE' as a consequence of increased experience of the IIF task, or partly influenced by the limited range of available numerical responses afforded by the CR-10 scale (0-10). The less commonly used CR-100 scale might have provided an alternative method given its greater measurement sensitivity and the added benefit of its association to a percentage scale (Borg and Kaijser, 2006). However, use of the CR-10 scale in the context of pacing and exercise regulation (Albertus et al., 2005; Joseph et al., 2008; Swart et al., 2009) would enable results of future studies to be compared against this existing research. In an attempt to provide continuity with the methods used to establish self-perceived capabilities in an ACL-reconstructed population (Chapter 3), a truncated PP utilising 3 constructs was trialled during the pilot-testing phase ahead of the current study. However, feedback from participants indicated that insufficient time was available during the IIF inter-set rest periods to enable appropriate consideration to be given to the PP and provide appropriate ratings for each construct. A VAS was ultimately employed to provide a measure of PTD, as the lack of objective units within this scale enabled application to an exercise task of any duration, and therefore negated any inter-individual differences in IIF performance. The ETL scale described by Garcin et al. (1999) has limited relevance to shorter duration activity (< 5 minutes) due to the inclusion of objective units of time. In addition, the ETL scale employs a question in which participants are asked "how long would you be able to perform an exercise at this intensity up to exhaustion?" In contrast, the VAS required participants to consider the question "how far from the end of the test do you think you are?" This required participants to estimate their performance not only in terms of time remaining, but also with regard to the amount of work completed. Although the question employed to obtain PTD potentially prompts a different cognitive challenge to that posed by the ETL scale, it is postulated that afferent feedback relating to the rate of muscle glycogen depletion during exercise is involved in the generation of a conscious RPE (Tucker, 2009), implying that performers do consider the amount of work already undertaken when making judgements concerning the regulation of exercise performance.

Whilst a robust approach was taken to minimise learning effects by the inclusion of a familiarisation session, the participants' prior experience of isometric exercise might still be limited in comparison to more common activities involving reciprocal patterns of muscle activation such as running and cycling. As such, the variation in both intra- and inter-individual perceptual response may be due in part to the nature of this novel exercise task. In order to establish the reliability of a measurement tool and the typical variability of responses, it is first important to ensure that the objects being measured are as stable as possible with respect to the attribute being measured. With regard to RPE, the importance of establishing reliability under identical repeated testing conditions has previously been emphasised (Lamb et al., 1999). The difficulty in exploring the current research question involves striking the correct balance between providing sufficient habituation without diminishing the relative novelty of the task. Given that prior experience is integral to both the generation of RPE (Noble and Robertson, 1996) and the subsequent selection of an appropriate pacing strategy (Tucker, 2009), the implementation of multiple testing sessions would theoretically increase experience and potentially alter the selected RPE values. Therefore, whilst repeated testing conditions may be identical, a performer's experience of a given exercise task and its associated perceptual cues will increase with repetition, thus modifying the perceptual-cognitive reference filter (Noble and Robertson, 1996) and altering the 'template RPE' (Tucker, 2009). For example, a learning effect has previously been demonstrated by Swart et al. (2009), who provided evidence of an increasingly linear RPE response accompanied by a concomitant increase in power output over the course of repeated cycling trials. In the current study, individuals with a training background that more closely mimics the metabolic demands of the IIF may, therefore, have been better placed to accurately interpret the associated afferent signals that contribute to RPE. Insufficient familiarity of the IIF would likely result in substantial learning effects and subsequently alter the 'template RPE' that would compromise the reliability of the perceptual measures. Alternatively, repeated exposure to the IIF task may produce a progressively more consistent and reliable RPE, but arguably provides less ecological validity with regard to resistance or rehabilitative exercise. In these environments, frequent manipulations of training variables are considered an integral component of programme design (Gamble, 2006; Grodski and Marks, 2008; van Grinsven et al., 2010), and the athlete or patient will, therefore, have limited exposure to a given mode of exercise before changes to intensity and/or duration are implemented. The familiarisation and habituation strategy in the current study was selected to minimise learning effects, yet provide a realistic scenario from which to ascertain the capability of self-perception measures to relate to TD in intermittent and isolated muscle exercise that may have application to rehabilitative or resistance training. In future studies, the inclusion of an IIF task performed to completion in the familiarisation session would possibly help to strike the correct balance between preserving the relative novelty of the exercise task whilst minimising any potential learning effects.

The logistics of participant recruitment and retention dictated that data collection for the current study was undertaken concurrently with that for the subsequent study (detailed in Chapter 5). Although the total time commitment for the current study was not excessive, participants were required to attend the laboratory on three occasions and to restrict their activity levels prior to assessment sessions. The original sample size of 16 was reduced to 8, due to participants failing to complete the assessment schedule or failing to adhere to the activity restrictions necessary to preserve the quality of data. On reflection, and given the importance of the current chapter in relation to the three subsequent studies (as detailed in Chapters 5 to 7), it would have been preferable to ensure greater numbers of participants completed the current study in order to improve its statistical power.

4.6. CONCLUSION

The purpose of the study was to evaluate the reliability of scales designed to measure RPE (via the CR-10 scale) and PTD during the performance of a novel intermittent isolated muscle exercise task. Whilst the composite V% measures indicate greater intra-individual variability than reported in previous studies, the composite ICC values suggest a good level of agreement between trials for both PTD and CR-10.

Having established a level of measurement precision to the CR-10 and PTD scales, this will now enable judgements to be made regarding experimental outcomes in subsequent studies described in Chapters 5 to 7. The capability of these scales to relate to TD can be therefore be explored in order to establish their validity and potential utility in regulating intermittent and static muscle exercise.

Chapter 5:
Congruency and responsiveness of perceived exertion and task duration during an intermittent isometric fatigue task

Poster Communication

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Shepherd, J., Gleeson, N. & Minshull, C. (2012). Congruency and responsiveness of perceived exertion and task duration during an intermittent isometric fatigue task.

CHAPTER 5: CONGRUENCY AND RESPONSIVENESS OF PERCEIVED EXERTION AND TASK DURATION DURING AN INTERMITTENT ISOMETRIC FATIGUE TASK

5.1. ABSTRACT

The aims of this study were (i) to investigate the relationship between measures of self-perception (perceived exertion; perceived task duration) and completed task duration in an intermittent isometric fatigue trial (IIF), and (ii) to evaluate the capability of two assessment paradigms (perceived exertion; perceived task duration) to reflect changes in IIF intensity. Fifteen participants performed two IIF tasks of the knee extensors at intensities of 60% and 70% of daily peak force, each separated by 48-72 hours. Ordering of the tasks was counter-balanced and participants were blinded to the precise intensity of each IIF. A category-ratio scale (CR-10) and visual analogue scale were used during each IIF task to record measures of perceived exertion and perceived task duration (PTD), respectively. Measures were recorded at 10% intervals across the relative duration of each IIF task. Pearson product-moment correlation coefficients revealed strong positive correlations ($r=0.99$; $p<0.01$) between completed task duration and both perceptual scales at the two IIF intensities. Visual inspection of the data revealed linear patterns of perceptual response in both IIF trials for both perceptual scales. Separate two-way repeated measures ANOVAs of CR-10 and PTD responses revealed significant main effects for time only ($F_{[2.2,30.1]} = 126.8$; $p<0.001$; $F_{[2.6,36.8]} = 117.2$; $p<0.001$, CR-10 and PTD, respectively). The results suggest that perceived exertion and perceived task duration are equally effective predictors of IIF end-point. However, neither measure was sufficiently responsive to discriminate between 10% changes in exercise intensity.

5.2. INTRODUCTION

Previous research has reported that RPE increases linearly in relation to TD during constant intensity running and cycling tasks (Horstman et al., 1979; Noakes 2004; Eston et al., 2007; Crewe et al., 2008). RPE might, therefore, be a useful predictor of TD (Eston et al., 2007), and cue the optimal adjustment of work-rate to enable both the preservation of homeostasis and achievement of the exercise task (Ulmer 1996).

While the relationship between RPE and TD has predominantly been investigated in running and cycling tasks, it is yet to be explored in resistance training or static and isolated muscle work that might generate different sensations of pain and fatigue and provide different perceptual cues (Noble and Robertson 1996). Isometric (static) exercises are commonly utilised during rehabilitation following reconstructive joint surgery, in order to minimise atrophy (Grodski and Marks, 2008) whilst simultaneously limiting movement and the transmission of excessive forces to the biologic tissue that has undergone surgical repair (Bailey et al., 2003; van Grinsven et al., 2010). Given the lack of current research involving isometric modes of exercise, it is unclear whether or not RPE would provide an accurate indicator of TD in these activities.

Accuracy in judging exercise pace is also a function of aptitude in discriminating between variations in work intensity. The anticipatory CGM theory stipulates that exercise is regulated by the generation of a conscious RPE that is subsequently matched against a 'template RPE', prompting any necessary adjustments in work-rate (Tucker, 2009). In accordance with this theory, an inability to accurately perceive variations in intensity during the performance of isolated muscle exercise tasks might provoke the selection of an inappropriate 'template RPE' against which to compare the demands of the task, and possibly result in a misinterpretation of capabilities and/or elicit the selection of an unsuitable training load. This might, in turn, exacerbate fatigue-related impairments to neuromuscular performance, such as decreased strength (Zebis et al., 2011), speed of force generating capabilities, delayed muscle response times (Minshull et al., 2007), and sub-optimal movement skill execution (McLean and Samorezov 2009). For example, previous research requiring participants to perform isometric knee extensions at a perceived intensity of 75% maximal voluntary contraction demonstrated relative errors in judgement of approximately 15% (West et al., 2005). Given that variations in relative work intensity of just 10% have been shown to result in significant changes to in power output (Thomas et al., 2007) and the number of repetitions performed (Shimano et al., 2006) during resistance training activities, a misperception of capabilities might plausibly impact upon PTD and expose performers to the unanticipated onset of fatigue.

A worst case-scenario of inaccurate perception could predispose an overestimation of capabilities that might expose athletes to fatigue-related impairments in neuromuscular performance that could potentially compromise dynamic joint stability (Minshull et al., 2012). Conversely, an underestimation of capabilities may lead to a sub-optimal level of performance. For example, novice weight trainers have been found to self-select training loads that are insufficient to promote health and fitness benefits typically associated with resistance training, such as increases in hypertrophy and strength (Glass and Stanton, 2004; Focht, 2007). The cumulative effect of repeated sub-optimal training sessions over a sustained period will result in a failure to achieve the desired exercise goals. For example, it is suggested that a lack of improvement in muscular conditioning due to sub-optimal resistance training may negatively impact upon long-term adherence to an exercise programme (Focht 2007). In a clinical context, such as a patient recovering from ACL-reconstructive surgery, a prolonged period of sub-optimal rehabilitation may provide inadequate stress to promote restored knee function and adaptation of the new graft (Marumo et al., 2005). This could result in increased physiotherapy costs and a delayed return to full activity, and may also lead to a lack of adherence to the programme.

Given the lack of current research involving isometric modes of exercise, it is unclear whether or not perceived exertion would provide an accurate indicator of TD in these types of activities. Before exploring this issue in an ACL-reconstructed population, it is of benefit to examine typical responses in an asymptomatic population, in order to provide a baseline from which to make future comparisons. The primary aim of this study was, therefore, to investigate the relationship between self-perception and TD in an intermittent isometric fatigue task (IIF) involving an isolated muscle group. A secondary aim was to evaluate the capability of two perceptual assessment paradigms (RPE; PTD) to discriminate between changes in work intensity.

5.3. METHODS

5.3.1. Participants

Fifteen recreationally active males (age 23.1 ± 3.7 years; height 181.3 ± 7.1cm; body mass 87.9 ± 9.3kg) provided written informed consent to participate in the study. All participants were asymptomatic of injury and were instructed to abstain from strenuous physical activity for the 24 hours preceding each testing session. The sample size was reduced from an initial sample of 23, as some participants failed to complete the full testing schedule while others were omitted due to a lack of adherence to the activity restrictions. Assessment protocols were approved by the Nottingham Trent University Ethical Committee for Human Testing. Sample participant information, consent form and health screen are included in Appendix C.

5.3.2. Experimental procedures and design

This was a controlled split-half cross-over blinded deception trial design. Participants were required to attend the laboratory on a total of four occasions, each separated by 48-72 hours. The first occasion involved familiarisation and accommodation to rapid maximum voluntary muscle activation (MVMA) of the quadriceps, and perceptual measures (described below). Also included was a brief exposure to an intermittent isometric fatigue task (IIF) for a total of 8 sets at an intensity of 60% daily peak force (PF). Occasion two served as a further familiarisation and habituation session whereby participants completed an entire IIF task at 60% daily PF, through to termination. These familiarisation sessions were included to provide exposure to and knowledge of the IIF, and to minimise any learning effects in subsequent testing sessions. The two remaining occasions served as assessment sessions, in which the participants were required to perform two conditions presented in a randomised counterbalanced order: i) IIF at 60% daily PF (IIF60) and ii) IIF at 70% daily PF (IIF70). Information regarding the precise intensity of each task was withheld from participants in order to explore whether the 10% difference in workload could be accurately perceived. This difference in exercise intensity exceeds the typical inter-session variability (V%) associated with indices of thigh muscle strength (Gleeson et al., 2002; Minshull et al., 2009; Chapter 4.3). Estimates of static volitional neuromuscular performance were obtained both prior to and immediately following the IIF.

5.3.3. Intermittent isometric fatigue task

The IIF protocol was performed in accordance with the description detailed in Chapter 4.2.3. Participants were 'blinded' to the precise magnitude of the target force

(60% or 70% baseline PF), but were able to observe and monitor in real-time how their efforts were matching the target line.

5.3.4. Perceptual measures

With the level of reliability for perceptual measures during an IIF having been established in Chapter 4, the utility of the relevant scales could therefore be investigated with regard to establishing their efficacy in providing an accurate prediction of TD. As such, measures of perceived exertion (CR-10) and perceived completed task duration (PTD) were recorded during each IIF inter-set rest period in accordance with the methods outlined in Chapter 4.2.4.

5.3.5. Assessment of neuromuscular performance

Participants performed 3 MVMAs in accordance with the procedures described in Chapter 4.2.5. Static peak force (PF) was recorded as the mean response of three intra-trial replicates in which the highest force was recorded in each trial. Rate of force development (RFD) was calculated for each intra-trial replicate as the average rate of force increase between 25% and 75% and reported as the mean response of the three replicates.

Electromyographic activity (EMG) was recorded from the m. vastus lateralis and m. vastus medialis during MVMAs using bipolar rectangular surface electrodes (self-adhesive, Ag/AgCl; 10 mm diameter, Unilect UK) that were positioned over the belly of the respective muscles. The inter-electrode distance was 30mm and a reference electrode was placed 30mm lateral and equidistant from the recording electrodes. The raw EMG signals were passed through a differential amplifier (1902 Mk IV; Cambridge Electronic Design, UK), input impedance 10,000 MΩ, CMRR 100 dB, gain 1000, and filtered (Butterworth [2nd order]; 1 kHz cut-off frequency). The signal, which incorporated minimal intrusion from induced currents associated with external electrical and electromagnetic sources and noise inherent in the remainder of the recording instrumentation, was analogue-to-digitally converted at 2.5 kHz sample rate, ensuring a significant margin of reserve between the highest frequency expected in the EMG signal and the Nyquist frequency and minimal intrusion from aliasing errors (Gleeson 2001). Standardised skin preparation methods yielded inter-electrode impedance of less than 5 kΩ. Electromechanical delay, defined as the time delay between the onset of electrical activity in the muscle and the onset of force production was calculated for the m. vastus lateralis and m. vastus medialis (EMD_{VL}; EMD_{VM}, respectively). The onset of electrical activity and muscle force were defined as the first point in time at each signal exceeded consistently the 95% confidence limits associated with the background electrical noise amplitude in quiescent muscle (Minshull et al., 2007).

5.3.6. Statistical analysis

All statistical analyses were performed using PASW v18.0 (SPSS Inc. Chicago, Il, USA). A paired samples t-test was used to explore differences in task duration between the two work intensities (IIF60 and IIF70). IIF duration values were log transformed (log 10) to satisfy assumptions of normality. Separate two (trial: IIF60; IIF70) by two (time: pre; post) fully repeated-measures ANOVAs were used to evaluate the effects of the IIF on each index of performance (PF, RFD, EMD_{VL} and EMD_{VM}).

Perceptual measures were obtained at 10% intervals of the completed task duration (CTD), with CR-10 and PTD scores at 10% to 100% of the IIF task subsequently used for analysis. For those individuals whose scores did not fall on a 10% interval, a cubic spline function enabled interpolation of a value that was subsequently used for analysis (Keele, 2008). Changes in CR-10 and PTD over the duration of the task under each condition of exercise intensity were analysed separately using two (trial: IIF60; IIF70) by ten (time: 10%; 20%; 30%; 40%; 50%; 60%; 70%;

80%; 90%; 100%) fully repeated-measures ANOVAs. Greenhouse-Geisser corrections were applied where assumptions of sphericity were violated, as indicated by $_{GG}$. Pearson product-moment correlation coefficients were used to explore the relationships between group mean perceptual responses (CR-10 and PTD) and completed task duration (CTD) at both work intensities. All data were analysed using standard descriptive statistics (mean ± SD), and statistical significance was accepted at $p<0.05$.

5.4. RESULTS

5.4.1. Perceptual measures

Group mean (± SD) and 95% confidence intervals (CI) for CR-10 and PTD responses measured over the duration of the IIF trials are presented in Table 5.1 and Table 5.2, respectively. Changes in CR-10 and PTD responses across time for both IIF tasks for both IIF tasks are illustrated in Figure 5.1 and Figure 5.2, respectively. A significant main effect for time revealed that both CR-10 responses ($F_{[2.2,30.1]} = 126.8$, $p<0.001$) and PTD responses ($F_{[2.6,36.8]} = 117.2$, $p<0.001$) progressively increased during both IIF60 and IIF70. There were no significant interaction effects or main effects for trial. Pearson product-moment correlation coefficients revealed strong positive correlations between CR-10 and CTD during both IIF60 ($r=0.990$, $p<0.01$) and IIF70 ($r=0.997$, $p<0.01$), and also between PTD and CTD during both IIF60 ($r=0.993$, $p<0.01$) and IIF70 ($r=0.996$, $p<0.01$).

Table 5.1 CR-10 responses (group means ± SD) and 95% CI during IIF60 and IIF70 (group means ± SD)

% of CTD	IIF60		IIF70	
	Mean ± SD	95% CI	Mean ± SD	95% CI
10	2.8 ± 1.8	1.9-3.7	2.1 ± 1.3	1.5-2.8
20	3.8 ± 2.2	2.7-4.9	3.2 ± 1.8	2.3-4.1
30	4.9 ± 1.9	3.9-5.9	4.1 ± 2.1	3.1-5.1
40	5.7 ± 2.1	4.6-6.7	4.9 ± 2.1	3.8-6.0
50	7.0 ± 1.9	6.1-8.0	5.8 ± 2.2	4.7-7.0
60	7.8 ± 1.5	7.0-8.5	6.8 ± 2.2	5.6-7.9
70	8.4 ± 1.4	7.6-9.1	7.7 ± 2.3	6.5-8.8
80	9.2 ± 1.2	8.6-9.8	8.5 ± 2.2	7.4-9.6
90	9.7 ± 0.5	9.5-10.1	9.1 ± 1.6	8.2-9.9
100	10.0 ± 0.0	n/a	9.6 ± 0.8	9.2-10.0

Table 5.2 PTD responses (group means ± SD) and 95% CI during IIF60 and IIF70 (group means ± SD)

% of CTD	IIF60		IIF70	
	Mean ± SD	95% CI	Mean ± SD	95% CI
10	23.6 ± 21.1	13.0-34.3	21.4 ± 13.1	14.8-28.1
20	33.9 ± 23.0	22.2-45.5	32.2 ± 18.2	23.0-41.4
30	43.9 ± 20.2	33.6-54.1	41.0 ± 20.5	30.6-51.4
40	55.4 ± 23.6	43.5-67.4	48.8 ± 21.3	38.0-59.6
50	64.0 ± 24.7	51.5-76.5	58.2 ± 22.2	47.0-69.5
60	73.2 ± 21.1	62.6-83.9	67.6 ± 21.9	56.5-78.7
70	79.0 ± 20.4	68.6-89.3	76.5 ± 22.6	65.0-87.9
80	87.8 ± 13.6	80.9-94.7	84.9 ± 22.1	73.7-96.1
90	93.6 ± 9.7	88.4-98.2	90.7 ± 16.4	82.3-99.0
100	97.5 ± 4.8	95.1-99.9	96.0 ± 8.3	91.8-100.2

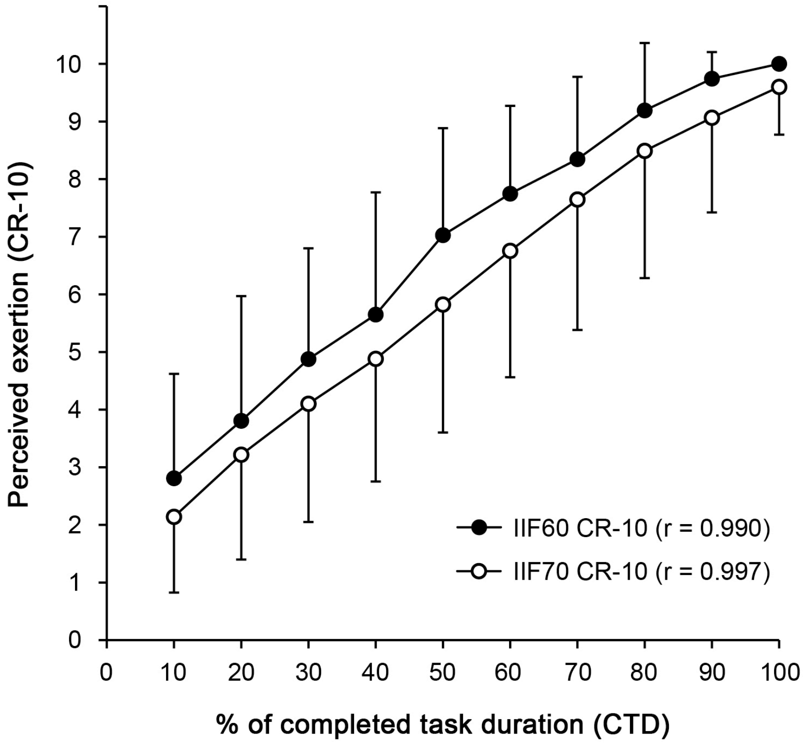

Figure 5.1 CR-10 responses during IIF60 and IIF70 (group mean ± SD)

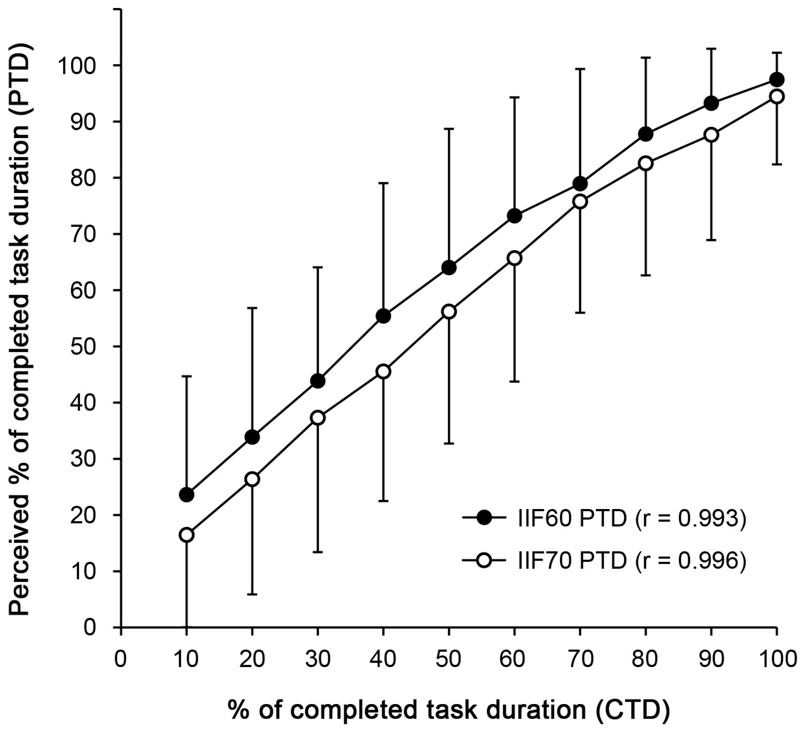

Figure 5.2 PTD responses during IIF60 and IIF70 (group mean ± SD)

5.4.2. Effects of the IIF intervention

A paired t-test revealed IIF60 duration to be significantly longer than IIF70 ($t_{[14]} = 2.5$, $p<0.05$) (reverse log transformed group mean set durations of 39.5 and 27.6 for IIF60 and IIF70, respectively). Group mean data for pre- and post-IIF indices of neuromuscular performance are presented in Table 5.3. A significant interaction for PF data ($F_{[1,14]} = 9.7$, $p<0.01$) revealed that both IIF tasks elicited significant reductions over time in PF compared to baseline levels, but these reductions were evident to a greater extent in the IIF60 task compared to the IIF70 task (group mean pre- to post-IIF PF reductions of 17.7% and 10.1%, respectively). Impairments to RFD performance were similar across both fatigue tasks ($F_{[1,14]} = 14.9$, $p<0.05$) (group mean RFD reductions of 23.4%). Performance of EMD_{VL} was improved following IIF60 (12.4%) but impaired following IIF70 (14.2%) ($F_{[1,14]} = 7.4$, $p<0.05$). No significant changes to EMD_{VM} performance were observed following either IIF task.

Table 5.3 Indices of neuromuscular performance for IIF60 and IIF70 (group means ± SD)

		IIF60			IIF70		
Index		Pre	Post	% change	Pre	Post	% change
PF	(N)	657.7 ± 111.8	545.2 ± 106.5	-17.1	641.5 ± 102.4	577 ± 105.9‡	-10.1‡
RFD	($N^{.s-1}$)	3240 ± 1100	2420 ± 1120	-25.3	3370 ± 1260	2640 ± 1400	-21.6
EMD_{VL}	(ms)	37.9 ± 12.6	33.2 ± 8.0	-12.4	31.0 ±5.5	35.4 ± 8.8‡‡	+14.2
EMD_{VM}	(ms)	35.4 ± 10.2	33.5 ± 7.5	-5.4	33.1 ± 6.2	36.2 ± 10.3	+9.4

‡Significant interaction between time and IIF intensity for PF ($p<0.05$)
‡‡Significant interaction between time and IIF intensity for EMD_{VL} ($p<0.05$)

5.5. DISCUSSION

The aim of this study was primarily to investigate the relationship and patterns of change between two different paradigms of self-perception involving RPE and PTD during an IIF, in order to establish the efficacy of these measures in predicting TD. The

IIF provoked significant fatigue as evidenced by 17.7% and 10% loss of strength following IIF60 and IIF70, respectively, and >23% reduction in RFD compared to baseline. The magnitude of these performance decrements is similar to those seen in sporting environments (Zebis et al., 2011).

During conditions of acute muscle fatigue, both CR-10 and PTD were observed to increase linearly in relation to CTD ($r=0.95$, $p<0.01$). This finding is consistent with previous research reporting a linear relationship between perceived exertion and CTD in cycling and running activities (Horstman et al., 1979; Noakes 2004; Eston et al., 2007; Crewe et al., 2008). The novel finding of a linear relationship during fatiguing activities in an isolated muscle group indicates that both perceptual scales have equal efficacy in predicting cessation of exercise. Inspection of the 95% CI ranges reveals a substantial variance in response for both the CR-10 and PTD scales (Table 5.2 and Table 5.3, respectively). It is, therefore, important to acknowledge that at any given point throughout the task a participant's perception may actually provide an under or over estimation of CTD. This has implications for accurately anticipating the development of fatigue and managing the associated decrements in performance. Although similar levels of variance have been evident in CR-10 responses obtained throughout cycling time trials (Albertus et al., 2005; Swart et al., 2009), it is not possible to directly compare the findings from the current study with much of the previous related literature due to the lack of consistency in the reporting of results.

This study also investigated the responsiveness of both models of perceptual assessment to a subtle but ecologically meaningful change in exercise intensity. In order to address this research question effectively, a controlled, blinded and deception trial design was employed with a split-half cross-over of exposure to the two levels of exercise intensity in order to ensure the minimisation of any carry-over effects. A concealed 10% difference in intensity between IIFs reflected what has previously been demonstrated in the literature as capable of provoking significant changes in exercise performance (Shimano et al., 2006; Thomas et al., 2007), and exceeds the inter-day random biological and technological variability reported for the isometric assessment of knee extension strength (4.9% to 6.6%: Gleeson et al., 2002; Chapter 4.3). Whilst this difference in intensity was sufficient to provoke statistically significant differences in the volume of exercise completed and decrements to PF, the results showed that there were no differences in either CR-10 or PTD between the two IIF tasks. Theoretically, a successful interpretation of a change in work intensity would see the pattern of PTD remain the same between tasks. In this respect, the group mean PTD responses during IIF60 and IIF70 demonstrated an equal utility in predicting TD in the current study. Conversely, if the CR-10 scale were to offer appropriate responsiveness, then a 10% change in work intensity should theoretically also provoke a concomitant change in RPE at the beginning of the IIF. However, the lack of significant difference in either CR-10 or PTD in the current study suggests that both approaches to the assessment of self-perception were unresponsive to relatively small changes in work intensity. This contrasts with previous research intimating that perceptions of effort using the CR-10 scale are capable of discriminating between 10% variations in work intensity during isometric knee extensor tasks (Pincivero et al., 2000). From the current findings, it is impossible to determine if the perceptual scales lacked sufficient sensitivity, or the participants were unable to perceive the change in intensity. Given that the inter-day variability of the CR-10 at 10% CTD of the IIF equated to 0.9 absolute measurement units (as discussed in Chapter 4), a greater differential between IIF work intensities may well be needed in order to establish the responsiveness of the scale.

The differences evident in neuromuscular performance in response to the altered work intensity were complex and potentially determined by the volume of work completed. The reductions in force were significantly greater in the lower intensity task

(17.7% and 10.1%, for IIF60 and IIF70, respectively). This finding may be partly explained by evidence of greater reductions in voluntary activation following low intensity vs. high intensity fatiguing activity (Behm and St-Pierre, 1997; Yoon et al., 2007). As such, fatigue at higher intensities has been primarily attributed to peripheral mechanisms within the muscle (Yoon et al., 2007). These may include depletion of intramuscular energy stores in conjunction with the accumulation of anaerobic metabolites such as inorganic phosphate (Nordlund et al., 2004) and potassium (Bangsbo et al., 1996). In contrast, a greater proportion of fatigue at lower intensities has been attributed to central mechanisms including inhibition resulting from the stimulation of group III and IV afferents (Garland, 1991) and reduced excitability of the motor neuron pool (Yoon et al., 2007). As such, the implementation of the twitch-interpolation technique via superimposed magnetic or electrical stimulation of the muscle nerve may have offered an insight into the potential contributions of peripheral and central fatigue (Paillard et al., 2005), and also help to provide an indication as to whether participants are fully motivated at the conclusion of each IIF trial. The interpolated twitch technique was pilot tested in an attempt to provide an indication as to the relative contributions of central and peripheral fatigue (Enoka, 2002). However, the pilot testing revealed that this technique was unable to be reliably reproduced, resulting in this assessment being omitted from the protocol. With the majority of participants having been recruited from a competitive rugby background, the group mean body mass index values were situated in the overweight category (>26), and could indicate greater levels of muscle tissue and/or body fat in some individuals. Increased fat tissue has been shown to reduce the capability to achieve supra-maximal responses during magnetically-evoked stimulation (Tomazin et al., 2011) and, therefore, may have contributed to some of the issues encountered in the current study. Additional methodological issues concerned with the interpolated twitch technique have previously been documented (Folland and Williams, 2007). Whilst force reductions were accompanied by similar impairments to RFD following both tasks (23.4%), the capability to initiate force, as estimated by EMD, showed a 12.4% improvement at the cessation of IIF60, versus a 14.2% impairment following IIF70. It has been previously theorised that isometric activations may induce reactive hyperaemia and associated distention of the involved muscle, which may result in decreased compliance of the series elastic component and thus preserve EMD performance (Minshull et al., 2007). Given that increased hyperaemia has been reported following isometric exercise both of increased duration (Osada et al., 2003) and increased intensity (Hunter et al., 2006), it is impossible to determine from the current results which of these factors may have provided a greater influence on EMD.

It should be noted that some elements of perceptual data violated assumptions of normality. These violations were only evident in a small proportion of the perceptual responses that were provided in the early and latter stages of the IIF, and consequently represented values at the lowest and highest points of the perceptual scales. The fixed end-points of the perceptual scales may have led to the skewing of this data and, therefore, caused this issue. Data transformations were unable to correct this problem, due to the fact that only a small minority of elements were non-normally distributed. Given that the current and subsequent studies represent exploratory investigations that focus on novel aspects of psycho-physiological fitness, the application of parametric statistics with a robustness to minor violations of underpinning assumptions was deemed an acceptable approach, given their greater experimental power in comparison to equivalent non-parametric methods (Rasch and Guiard, 2004).

5.6. CONCLUSION

In summary, the current findings suggest that RPE (measured through CR-10) and PTD increase linearly in relation to CTD during an intermittent isometric fatiguing task performed at both 60% and 70% daily PF. However, the variance of the group responses have possible implications for the utility of the scales in predicting CTD during this mode of exercise on an individual basis. The lack of any significant difference between the CR-10 values obtained during IIF60 and IIF70 would suggest that the scale was not sufficiently responsive to discriminate between a 10% change in exercise stress. Indeed, the level of sensitivity of the CR-10 scale may be limited to detecting force differentials of a greater magnitude. A greater differential between IIF work intensities may, therefore, be required in order to help establish the responsiveness of the CR-10 scale. This larger IIF target force differential would still retain ecological validity in the context of rehabilitative exercise, considering the changes in PF values from pre-surgery to 6-weeks post-surgery in an ACL-reconstructed limb (group mean reductions of ~27% to 35%: results detailed in Chapter 3.3), and also the disparity between PF values attributed to the ACL-reconstructed limb and the uninvolved limb (uninvolved limb ~33% to 43% stronger: results detailed in Chapter 3.3).

Chapter 6:
Effect of a substantial variation in work intensity on perceived exertion and ask duration during an intermittent isometric fatigue task

CHAPTER 6: EFFECT OF A SUBSTANTIAL VARIATION IN WORK INTENSITY ON PERCEIVED EXERTION AND TASK DURATION DURING AN INTERMITTENT ISOMETRIC FATIGUE TASK

6.1. ABSTRACT

The aim of this study was to evaluate the capability of two perceptual assessment paradigms (perceived exertion; perceived task duration) to reflect a 20% differential in IIF work intensity, and if this variation in target force impacts upon the relationship and pattern of perceptual response in relation to task duration. Eighteen university level male rugby players performed two conditions, each separated by 1 hour and presented in a randomised counterbalanced order: i) intermittent isometric fatigue trial (IIF) at 60% baseline peak force (IIF60); ii) IIF at 80% baseline peak force (IIF80). A category-ratio scale (CR-10) and visual analogue scale were used during each IIF task to record measures of perceived exertion and perceived task duration, respectively. Measures were recorded at 10% intervals across the relative duration of each IIF task. A two-way repeated measures ANOVA revealed a significant interaction between trial and time, with CR-10 responses across the first three sets of IIF80 found to be significantly higher and increase at a faster rate in comparison to the equivalent responses for IIF60 ($F_{[2,34]}$ =4.7; $p<0.05$), thus reflecting the 20% differential between target forces. However, visual inspection of the data revealed an apparent curvilinear trend in perceptual responses throughout the IIF60 trial that contrasts with previous findings. These findings question the accuracy of self-perception to act as a predictor of task duration during intermittent isometric exercise tasks.

6.2. INTRODUCTION

The previous investigation (Chapter 5) discovered that both RPE (utilising a CR-10 scale) and perceived completed task duration (PTD) exhibited a linear relationship with the percentage of completed task duration (CTD) during an IIF in the knee extensors. These findings are in support of previous research using different exercise modalities, which shows ratings of perceived exertion to increase linearly in relation to TD during constant intensity running, walking and cycling tasks (Morgan and Borg 1976; Horstman et al., 1979; Noakes 2004; Eston et al., 2007; Crewe et al., 2008; Davies et al., 2009). These paradigms of self-perception may, therefore, be able to act as predictors of TD in intermittent static muscle activity, and have potential application for the self-regulation of performance during rehabilitative and resistance exercise. However, some caution should be applied when adopting these conclusions due to the large standard deviations evident in the group responses. Indeed, similar levels of variance have been evident in CR-10 responses obtained at discrete time-points during cycling time trials (Albertus et al., 2005; Swart et al., 2009).

Whilst a 10% variation in IIF intensity was sufficient to cause a significant difference in task duration in the previous investigation detailed in Chapter 5, it appeared to have minimal influence on the reported self-perception values. As such, both the CR-10 and PTD scales demonstrated equal efficacy in reflecting TD at both exercise intensities. However, a 10% increase in work intensity was expected to have provoked a greater RPE and thus a higher CR-10 response at the beginning of IIF70 in comparison to IIF60. The lack of significant difference in CR-10 responses between trials implies that the 10% differential in magnitude during the present exercise task was insufficient to be detected by the participants. This contrasts with previous research reporting that the CR-10 scale can reflect 10% changes in muscle activation intensity during isometric knee extensions (Pincivero et al., 2000).

Considering the recommendation of RPE in exercise prescription as a method of monitoring workload (Noble and Robertson, 1996; Pincivero et al., 2000), it is especially important for performers to be able to accurately perceive intensity. This ability has been tested in a research setting through studies designed to deceive participants and withhold precise exercise information (Hampson et al., 2004; Yunoki et al., 2009; Pires and Hammond, 2012). When performers are misinformed regarding exercise task demands, it is theorised that any change in RPE would result from a mismatch between the initially anticipated and newly imposed workload (Baden et al., 2005). Given the potential importance of RPE in regulating exercise performance (Tucker, 2009; Noakes, 2011), a misjudgement may prompt the selection of an inappropriate 'template RPE' against which the perceived demands and anticipated duration of a given exercise task are compared, ultimately compromising the adopted pacing strategy. There is, however, conflicting evidence as to the impact upon RPE resulting from the withholding of information or deliberate deception concerning exercise intensity. Hampson et al. (2004) reported a tendency towards elevated RPE in runners who were deceived into anticipating a harder level of activity than actually performed. Conversely, RPE was found to be unaffected in cyclists who were misled into expecting an easier level of activity than they were subsequently required to perform (Yunoki et al., 2009). Pires and Hammond (2012) reported similar findings, after deceiving participants that they would be cycling at a lower intensity than the actual workload. There is the possibility that social factors within a testing environment may prompt the participant to under-report their exertion in order to appear more capable (Lewthwaite 1990). However, the findings from Yunoki et al. (2009) and Pires and Hammond (2012) suggest that participants were able to interpret the afferent cues associated with performing exercise at a higher intensity, and formulate an appropriate RPE response that reflected the demands of the task.

In practical terms, the ability to detect changes in work intensity is particularly important for individuals who may have to perform an exercise programme without specialist supervision. For example, a review by Coppola and Collins (2009) into the relative merits of supervised physiotherapy versus predominantly unsupervised home exercise highlighted that even those patients benefitting from regular supervision only received up to 20 sessions during a post-operative ACL rehabilitation period that may last as long as 9 months. The majority of patients recovering from ACL-reconstructive surgery will, therefore, have limited contact time with a physiotherapist, and will be required to self-regulate much of their rehabilitation. Post-operative ACL rehabilitation programmes are characterised by progressive increases in intensity and a gradual re-introduction of dynamic exercise in order to optimise recovery and prepare the patient for a return to full activity (van Grinsven et al., 2010). The patient will thus be prescribed a variety of rehabilitation exercises and sessions, and must accurately interpret the sensations of exertion to make judgements concerning intensity and appropriate pacing during isolated muscle exercise, commensurate with the advice of the physiotherapist. It is prudent to first establish whether an asymptomatic population has the capacity to detect changes in work intensity and utilise this perception in predicting TD, before applying this principle to a patient population.

Results from the previous study (Chapter 5) showed that a 10% differential in exercise intensity was not distinguishable by the CR-10 scale. However, there is still merit in assessing the measurement sensitivity of the CR-10 by employing a larger IIF target force differential. An increase in the magnitude of the work intensity differential has relevance to a clinical setting, where patients may have experienced substantial impairments to neuromuscular performance following surgery. Indeed, changes in PF as a consequence of ACL-reconstructive surgery are characterised by significant reductions in the reconstructed limb from pre-surgery to 6-weeks post-surgery (~27% to 35%: results detailed in Chapter 3.3). In addition, there is a substantial disparity between the strength levels of the reconstructed limb and the uninvolved limb of ~33% to 43% (Chapter 3.3). In this situation it is important for the patient to be able to accurately detect the capabilities of their reconstructed limb, in order to implement this information with a view to predicting and regulating their exercise performance.

The aim of this study was to evaluate the capability of each assessment paradigm (RPE; PTD) to reflect a 20% differential in IIF work intensity, and if this greater variation in target force impacts upon the relationship and pattern of perceptual response in relation to TD.

6.3. METHODS

6.3.1. Participants

Eighteen university level male rugby players (age 20.6 ± 1.9 years; height 176.8 ± 6.1cm; body mass 82.9 ± 11.4kg) gave their written informed consent to participate in the study. The decision to select participants from a similar athletic population was taken in an attempt to increase the homogeneity of the sample. All participants were asymptomatic of injury and were instructed to abstain from strenuous physical activity for the 24 hours preceding each testing session. The sample size was reduced from an initial sample of 23, as some participants failed to complete the full testing schedule while others were omitted due to a lack of adherence to the activity restrictions. Assessment protocols were approved by the Nottingham Trent University Ethical Committee for Human Testing.

6.3.2. Experimental procedures and design

The study was a controlled split-half cross-over blinded deception trial design. Participants were required to attend the laboratory on a total of two occasions. The first occasion involved familiarisation and accommodation to rapid maximum voluntary muscle activation (MVMA) of the quadriceps, and perceptual measures (described below). Also included was an exposure to the IIF, whereby participants completed an entire IIF at 60% baseline peak force (PF), through to termination. This familiarisation session was incorporated to provide exposure to and knowledge of the assessment protocols and IIF task to ensure minimisation of any systematic and learning effects in the subsequent assessment session. The remaining laboratory visit was performed 48 hours subsequent to familiarisation and served as the assessment session. This session required the participants to perform two conditions, each separated by 1 hour and presented in a randomised counterbalanced order: i) IIF at 60% baseline PF (IIF60); ii) IIF at 80% baseline PF (IIF80). Information regarding the precise intensity of each task was withheld from participants in order to explore whether or not the 20% difference in workload could be accurately perceived. Following a standardised warm-up of five minutes cycle ergometry performed at 90 W, and an additional five minutes of stretching of the involved musculature, participants were secured in a seated position on a custom built dynamometer in accordance with the specifications outlined in Chapter 4. Estimates of magnetically evoked and volitional neuromuscular performance were obtained both prior to and immediately after each IIF.

6.3.3. Intermittent isometric fatigue task

The IIF protocol was performed in accordance with the description detailed in Chapter 4. Participants were ‘blinded’ to the precise magnitude of the target force (60%

or 80% baseline PF), but were able to observe in real-time how their efforts were matching the target line.

6.3.4. Perceptual measures

Measures of perceived exertion (CR-10) and perceived percentage of completed task duration (PTD) were recorded during each IIF inter-set rest period in accordance with the methods outlined in Chapter 4.2.4. Presentation of the scales was randomised in order to minimise any influence of the order on the participants' current perception.

6.3.5. Assessment of neuromuscular performance

Magnetically-evoked twitch responses from the knee extensors were obtained from supra-maximal magnetic stimulation of the femoral nerve achieved by means of double wound coil powered by two Magstim 200 stimulators connected via a Bi-Stim module with zero inter-pulse interval (Magstim Co. Ltd., Whitland, Dyfed, Wales). The optimum site for stimulation of the nerve was defined as the site that elicited the largest twitch force and M-wave amplitude. The magnetic coil was placed in the femoral triangle just lateral to the femoral artery, then small iterative positional changes of the coil were made that were commensurate with increasing size of responses during a series of discrete stimulations. The optimised coil position was then maintained manually throughout the duration of the testing. The protocol deployed to elicit and verify supra-maximal stimulation was in accordance with the methodology described previously by Minshull et al. (2007) whereby supra-maximal stimulation was defined as the intensity of stimulation at which there was subsequently no more than a 5% increase in M-wave peak amplitude and peak twitch force despite a 10% or greater increase in the intensity of stimulation. Supra-maximal stimulation was verified by contemporaneous visual inspection of the data during a sequence of seven discrete stimulations of increasing intensity that commenced at 40% of the Magstim 200's maximal capacity output with subsequent increments of 10% to 100% of capacity and by retrospective analyses of M-wave. Each stimulation in the sequence was separated by at least 10 s to ensure sufficient neuromuscular recovery (Moore and Kukulka 1991). Indices of magnetically-evoked neuromuscular performance were obtained from three supra-maximal stimulations. Supra-maximal stimulation was not obtainable in all cases. This may have been due to greater levels of fat tissue present in some individuals (Tomazin et al., 2011). As such, data from 15 participants is presented.

Following a series of sub-maximal warm-up muscle activations an auditory signal was delivered randomly within 1-4 seconds cuing the participant to extend their knee as rapidly and forcefully as possible against the immovable restraint provided by the apparatus. Another auditory signal was then given to the participant after approximately 3 seconds of maximal voluntary muscle activation (MVMA) to cue muscular relaxation. Three trials were performed, each separated by a minimum of 10 s.

Volitional static peak force (PF_V) and magnetically-evoked peak twitch force (P_TF_E) were recorded as the mean response of three intra-trial replicates in which the highest force was recorded in each trial. Volitional rate of force development (RFD) was calculated for each intra-trial replicate as the average rate of force increase between 25% and 75% PF_V. Magnetically-evoked rate of force development (RFD_E) was calculated for each intra-trial replicate as the average rate of force increase between the onset of force production and P_TF_E. The mean response of the three replicates was used to describe performance.

Electromyographic activity (EMG) was recorded from the m. vastus lateralis and m. vastus medialis during MVMAs in accordance with the procedures outlined in Chapter 4. Volitional ($EMD_{VL;}$ EMD_{VM}) and magnetically evoked ($EMD_{VLE;}$ EMD_{VME}) electromechanical delay were defined as the time delay between the onset of electrical activity in the muscle and the onset of force production. The onset of electrical activity and muscle force were defined as the first point in time at each signal exceeded consistently the 95% confidence limits associated with the background electrical noise amplitude in quiescent muscle (Minshull et al., 2007).

6.3.6. Statistical analysis

All statistical analyses were performed using PASW v18.0 (SPSS Inc. Chicago, Il, USA). Perceptual measures were obtained at 10% intervals of the completed task duration (CTD), with CR-10 and PTD scores at 10% to 100% of the IIF task subsequently used for analysis. For those individuals whose scores did not fall on a 10% interval, a cubic spline function enabled interpolation of a value that was subsequently used for analysis (Keele, 2008). Changes in CR-10 and PTD over the duration of the IIF task (measures obtained at 10% intervals throughout the relative duration of the IIF, from 10% to 100% of the IIF) under each exercise intensity were analysed separately using two (trial: IIF60; IIF80) by ten (time: 10%; 20%; 30%; 40%; 50%; 60%; 70%; 80%; 90%; 100%) fully repeated-measures ANOVAs. Greenhouse-Geisser corrections were applied where assumptions of sphericity were violated, as indicated by $_{GG}$. Post hoc analysis using paired sample t-tests were performed in order to confirm significant differences between trials for specific time points, with an adjustment made via the Holm-Bonferroni correction to protect against type 1 error. Pearson product-moment correlation coefficients were used to explore the relationships between group mean perceptual responses (CR-10 and PTD) with the percentage of completed task duration (CTD) at each work intensity (IIF60 and IIF80).

It was evident that the shorter duration of IIF80 would typically provide fewer than 10 opportunities to obtain perceptual responses, which would offer limited data that could be used for subsequent analysis (for example, the first opportunity to record a perceptual response during IIF80 may equate to a relative time-point of 25% CTD). It was, therefore, necessary to use an alternative method of analysis in order to investigate the initial CR-10 response to the change in work intensity. CR-10 measures from the first three sets of each IIF trial were analysed using a two (trial: IIF60; IIF80) by three (sets: 1; 2; 3) fully repeated-measures ANOVA. Post hoc paired sample t-tests with Holm-Bonferroni corrections were again performed in order to confirm significant differences between trials for specific sets.

Separate two (trial: IIF60; IIF80) by two (time: pre; post) fully repeated-measures analyses of variance (ANOVA)s were used to evaluate the effects of the IIF on each index of performance (PF; RFD; EMD_{VL}; EMD_{VM}; P_TF_E; RFD_E; EMD_{VLE}; EMD_{VME}). A paired samples t-test was used to explore differences in IIF trial duration between the two work intensities (IIF60 and IIF80).

All data were analysed using standard descriptive statistics (mean ± SD), and statistical significance was accepted at $p<0.05$.

6.4. RESULTS

6.4.1. Perceptual measures

Initial CR-10 responses for the first three sets of IIF60 and IIF80 trials are illustrated in Figure 6.1. Analysis revealed a significant interaction between trial and time, with CR-10 responses for IIF80 to be significantly higher and increase at a faster rate in comparison to the equivalent responses for IIF60 ($F_{[2,34]} =4.7$; $p<0.05$).

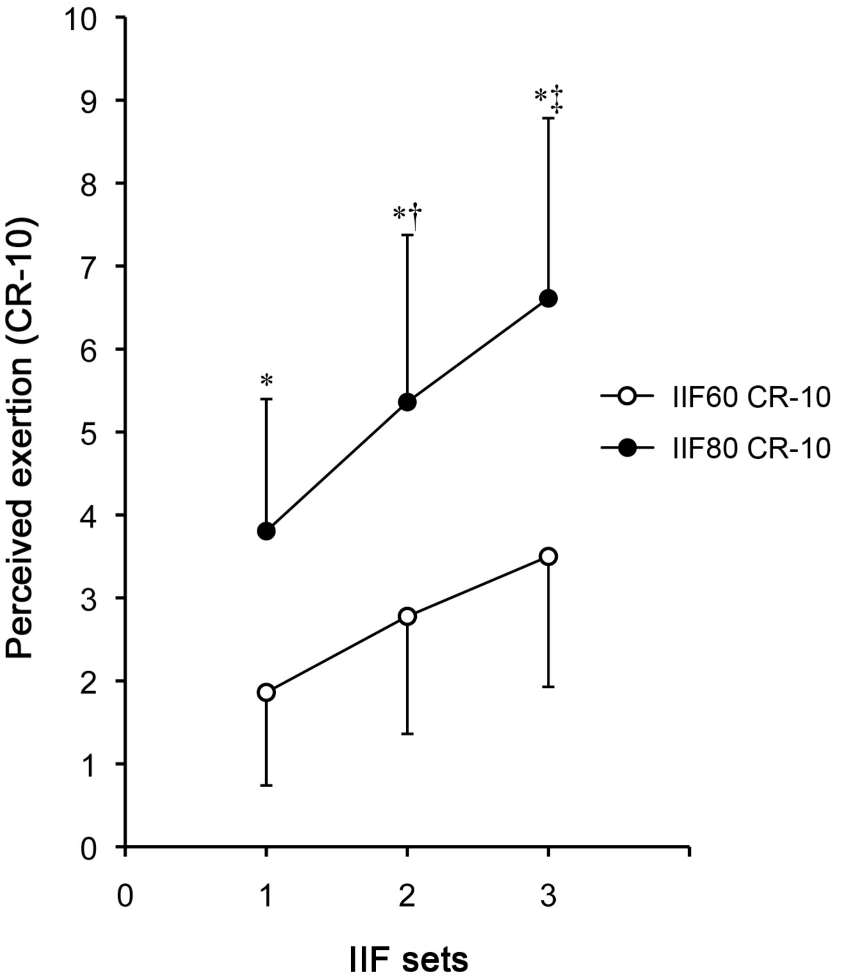

Figure 6.1 Initial CR-10 responses during IIF60 and IIF80 (group means ± SD)
*Significant difference between IIF60 and IIF80 ($p<0.001$)
†Significantly different to Set 1 and Set 3 ($p<0.001$)
‡Significantly different to Set 1 and Set 2 ($p<0.001$)

Group mean (± SD) and 95% confidence intervals (CI) for PTD responses measured over the duration of the IIF60 and IIF80 trials are presented in Table 6.1. Changes in PTD across both IIF60 and IIF80 trials are illustrated in Figure 6.2. Analyses revealed a significant main effect for both time ($F_{[2.5,43.3\ GG]} = 257.1$; $p<0.001$) and trial ($F_{[1,17]} = 7.6$; $p<0.05$) with PTD responses for IIF60 consistently higher than the corresponding values for IIF80 throughout the entire trial. Pearson product-moment correlation coefficients revealed strong positive correlations between PTD and CTD during both IIF60 ($r=0.977$; $p<0.001$), and IIF80 ($r=0.997$; $p<0.001$) indicating strong linear relationships.

Table 6.1 PTD responses (group means ± SD) and 95% CI during IIF60 and IIF80

	IIF60		**IIF80**	
% of CTD	Mean ± SD	95% CI	Mean ± SD	95% CI
10	22.9 ± 12.9	16.9-28.9	18.0 ± 12.4	12.2-23.7
20	38.9 ± 19.5	29.8-47.9	27.7 ± 14.6	21.0-34.5
30	50.6 ± 23.2	39.9-61.3	37.5 ± 17.9	29.2-45.7
40	62.3 ± 22.1	52.1-72.6	45.2 ± 18.3	36.7-53.6
50	69.6 ± 22.8	59.1-80.1	53.3 ± 18.3	44.9-61.7
60	78.2 ± 17.2	70.2-86.1	62.7 ± 18.4	54.2-71.2
70	86.0 ± 10.8	81.1-91.0	69.3 ± 18.4	60.8-77.8
80	90.7 ± 9.2	86.5-94.9	74.4 ± 18.2	66.0-82.8
90	94.4 ± 6.5	91.4-97.5	81.3 ± 14.4	74.6-87.9
100	98.3 ± 3.6	96.6-100.0	89.3 ± 13.0	83.3-95.4

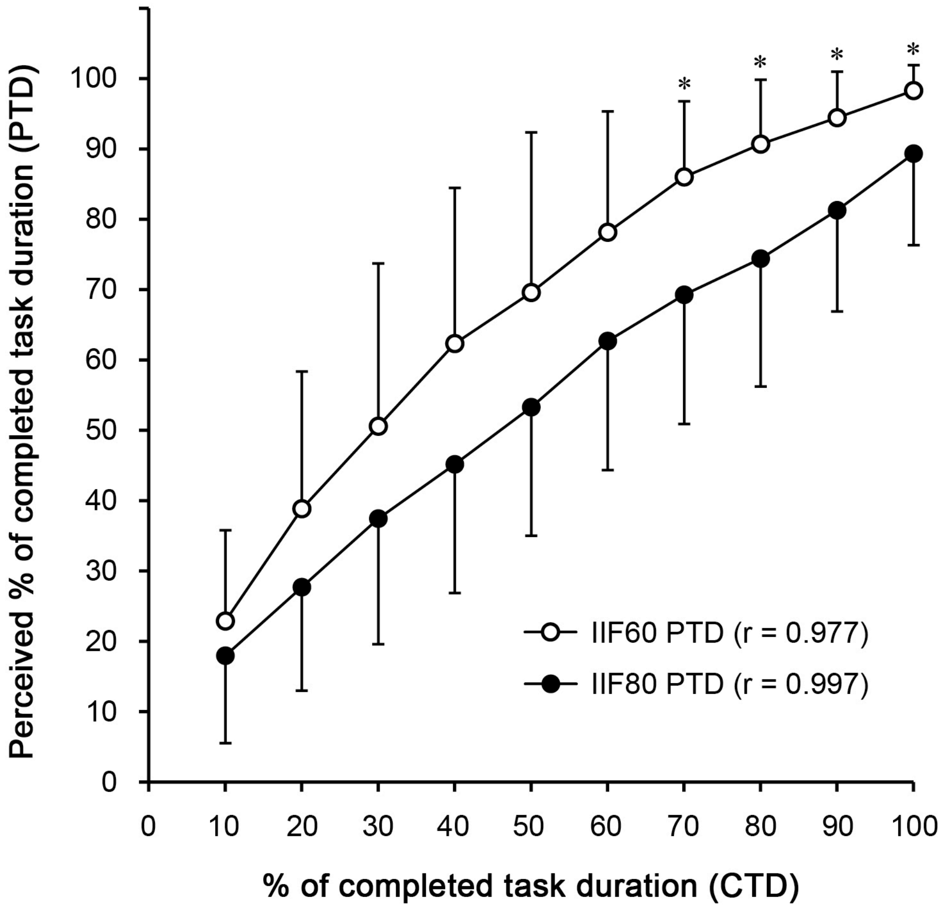

Figure 6.2 PTD responses during IIF60 and IIF80 (group means ± SD)
*Significant difference between IIF60 and IIF80 ($p<0.05$)

Group mean (± SD) and 95% confidence intervals (CI) for CR-10 responses IIF60 and IIF80 are presented in Table 6.2. Figure 6.3 illustrates the change in CR-10 responses across time for both IIF60 and IIF80 trials. Analyses revealed a significant main effect for both time ($F_{[2.2,38.2\ GG]}=188.1$; $p<0.001$) and trial ($F_{[1,17]}=7.3$; $p<0.05$) with CR-10 responses for IIF60 higher than the corresponding values for IIF80 when expressed at 10% intervals of CTD. Pearson product-moment correlation coefficients revealed strong positive correlations between CR-10 and CTD during both IIF60 ($r=0.957$; $p<0.001$), and IIF80 ($r=0.996$; $p<0.001$) indicating strong linear relationships.

Table 6.2 CR-10 responses (group means ± SD) and 95% CI during IIF60 and IIF80

	IIF60		**IIF80**	
% of CTD	Mean ± SD	95% CI	Mean ± SD	95% CI
10	3.2 ± 1.4	2.6-3.8	3.1 ± 1.7	2.4-3.9
20	4.8 ± 1.9	3.9-5.7	3.9 ± 1.6	3.2-4.6
30	6.1 ± 2.1	5.1-7.1	4.9 ± 1.7	4.1-5.6
40	7.3 ± 2.0	6.2-8.0	5.7 ± 1.6	4.9-6.4
50	7.9 ± 1.7	7.1-8.6	6.4 ± 1.6	5.7-7.1
60	8.4 ± 1.6	7.7-8.4	7.2 ± 1.6	6.4-7.9
70	9.0 ± 1.0	8.5-9.4	7.9 ± 1.3	7.3-8.5
80	9.4 ± 0.8	9.0-9.8	8.5 ± 1.2	7.9-9.0
90	9.7 ± 0.7	9.3-10.0	9.0 ± 1.0	8.6-9.5
100	9.8 ± 0.7	9.5-10.2	9.6 ± 0.7	9.2-9.9

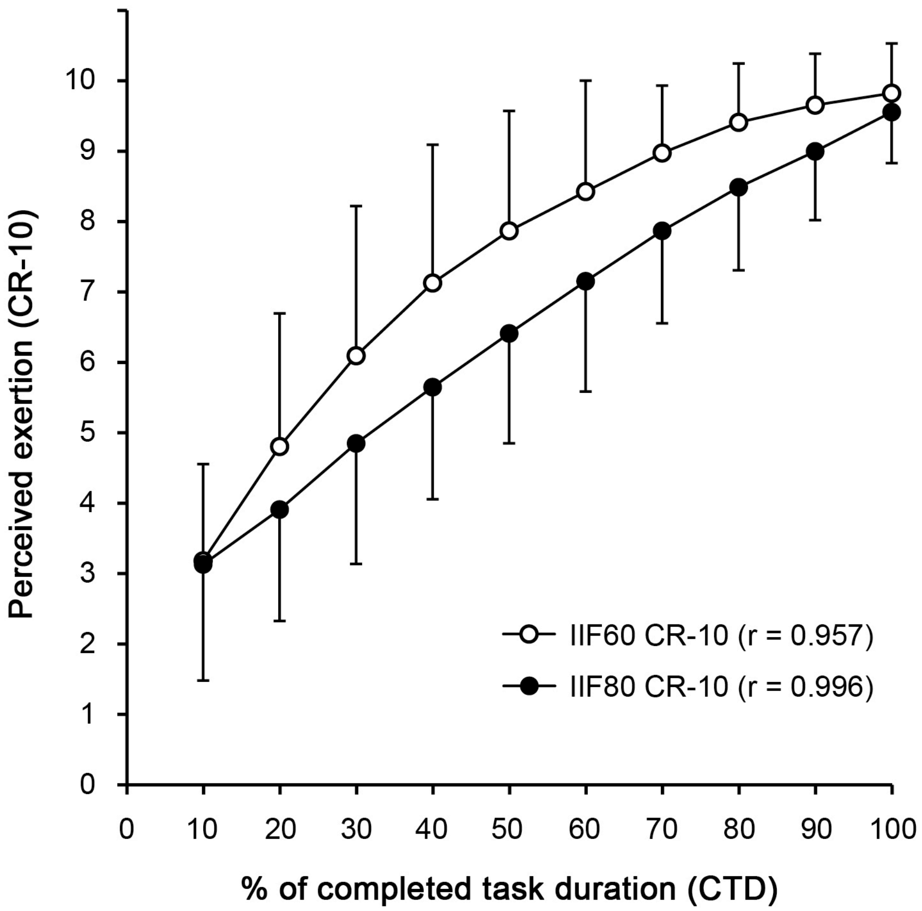

Figure 6.3 CR-10 responses during IIF60 and IIF80 (group means ± SD)

6.4.2. Effects of the IIF intervention

The results of the paired t-test revealed IIF60 duration to be significantly longer than IIF80 (group mean IIF durations of 27.2 ± 22.1 and 6.3 ± 2.9 sets for IIF60 and IIF80, respectively; 76.7% fewer sets completed in IIF80) ($t=_{[17]}4.2$, $p<0.001$).

6.4.2.1. Volitional neuromuscular performance

Group mean data for pre- and post-IIF indices of volitional neuromuscular performance are presented in Table 6.3. A significant interaction associated with the two-way repeated measures ANOVA for PF data ($F_{[1,17]}=7.9$; $p<0.05$) revealed that both IIF tasks elicited reductions in PF compared to baseline levels, but to a greater extent in the IIF60 task compared to the IIF80 task (group mean pre- to post-IIF PF reductions of 16.5% and 10.1%, respectively. Compared to baseline levels, both IIF tasks led to similar reductions in RFD ($F_{[1,17]}=10.3$; $p<0.01$) (group mean pre- to post-IIF RFD reductions of 20.9%). No significant changes to EMD_{VL} or EMD_{VM} performance were observed following either IIF trial.

Table 6.3 Indices of volitional neuromuscular performance for IIF60 and IIF80 (group means ± SD)

Index		IIF60			IIF80		
		Pre	Post	% change	Pre	Post	% change
PF	(N)	618.4 ± 144.9	516.6 ± 139.6	-16.5	614.8 ± 144.1	552.6 ± 147.9	-10.3*
RFD	($N^{.s-1}$)	3931 ± 1522	3129 ± 1497	-20.4	4150 ± 1549	3262 ± 1302	-21.4
EMD_{VL}	(ms)	35.4 ± 6.1	34.1 ± 4.6	-3.7	35.6 ± 6.5	35.5 ± 5.5	-0.3
EMD_{VM}	(ms)	33.6 ± 5.6	31.9 ± 3.6	-5.1	33.6± 7.7	32.9 ± 4.3	-2.1

*Significant interaction between time and IIF intensity (p<0.05)

6.4.2.2. Evoked neuromuscular performance

Group mean data for pre- and post-IIF indices of evoked neuromuscular performance are presented in Table 6.4. The two-way repeated measures ANOVA for P_TF_E data, ($F_{[1,14]}=8.7$; $p<0.01$) revealed that both IIF tasks led to improvements in P_TF_E but to a greater extent following the IIF80 task compared to the IIF60 task (group mean pre- to post-IIF P_TF_E increases of 24.7% and 51.1%, for IIF60 and IIF80 respectively). A similar interaction was evident in the results for RFD_E, with greater increases evident following IIF80 in comparison to IIF60 ($F_{[1,14]}$ =5.8; $p<0.05$) (group mean pre- to post-IIF RFD increases of 83.5% and 120.9%, for IIF60 and IIF80 respectively). Significant main effects for time were evident for both EMD_{VLE} ($F_{[1,14]}$ =19.2; $p<0.001$) (group mean pre- to post-IIF performance improvements of 6%) and EMD_{VME} ($F_{[1,14]}$ =11.2; $p<0.01$) (group mean pre- to post-IIF performance improvements of 5.8%).

Table 6.4 Indices of evoked neuromuscular performance for IIF60 and IIF80 (group means ± SD)

Index		IIF60 Pre	IIF60 Post	IIF60 % change	IIF80 Pre	IIF80 Post	IIF80 % change
P_TF_E	(N)	94.8 ± 25.5	118.2 ± 31.6	+24.7	87.7 ± 22.6	132.5 ± 32.6	+51.1*
RFD_E	($N^{.s-1}$)	1329 ± 379	2439 ± 799	+83.5	1261 ± 332	2786 ± 862	+120.9†
EMD_{VLE}	(ms)	15.9 ± 1.5	15.1 ± 1.7	-5.0	16.0 ± 1.6	14.9 ± 1.0	-6.9
EMD_{VME}	(ms)	14.6 ± 1.6	14.0 ± 1.7	-4.1	14.6 ± 1.6	13.5 ± 0.9	-7.5

*Significant interaction between time and IIF intensity ($p<0.01$)
†Significant interaction between time and IIF intensity ($p<0.05$)

6.5. DISCUSSION

A key finding from this study was that the initial CR-10 responses (as recorded following the first three IIF sets) were higher during IIF80 versus IIF60, reflecting the greater exercise intensity (illustrated in Figure 6.1). Thus, it appears as though the CR-10 is sufficiently sensitive to detect the 20% differential between work intensities in the current exercise modality. Moreover, the rate of increase of CR-10 response was also significantly greater in the initial stages of the IIF80 trial, thus reflecting the higher intensity of this shorter duration task. The conscious perception of variations in work intensity should theoretically enable the subconscious selection of an appropriate 'template RPE', against which to compare the various afferent cues and anticipated task demands. In the context of the current investigation, the results would suggest that participants were able to perceive the larger 20% variation in IIF intensity, and thus provide a more accurate basis from which to inform their subsequent judgments pertaining to CTD.

Strong positive correlations between each paradigm of self-perception and CTD were evident in both the IIF60 and IIF80 tasks ($r=0.96$; $p < 0.001$), suggesting that both RPE and PTD may provide an accurate indication of exhaustion time. However, significant differences in perceptual responses were evident between trials, with both CR-10 and PTD values during IIF60 higher than the responses recorded during IIF80 at the equivalent percentage of CTD. Furthermore, visual inspection of the IIF60 mean responses would suggest a trend towards a curvilinear relationship in comparison to the IIF80 task (Figures 3 and 4). This finding is contrary to results from the previous study, whereby group mean perceptual responses appeared to increase linearly in relation to CTD. The linear relationship with CTD has been provided as evidence in support of the role of RPE in anticipatory regulation of exercise (Noakes, 2004; Tucker, 2009). The generation of RPE at the beginning of an exercise bout is used to establish a work-rate that is continually re-calculated based on the interpretation of afferent feedback with regard to the anticipated end-point (St Clair Gibson et al 2006). In accordance with this theory, RPE may act as a useful predictor of task duration (Eston et al., 2007; Noakes, 2008). However, in the presence of a curvilinear relationship such as that observed in the IIF60 trial, self-perception would provide an underestimation of TD, potentially leading to premature termination of the exercise task and therefore contributing to a sub-optimal performance. The linear patterns of response during IIF80 are consistent with those observed in the previous study. However, in the case of PTD, the greater linearity of the data does not necessarily equate to an improved capacity to predict TD, as the group mean response at completion was only 89.3% PTD, suggesting that participants reached the termination point of the task 10% earlier than expected. The magnitude of this differential exceeds the intra-individual variability of PTD at cessation of IIF (1.5%) as reported in Chapter 4. This unanticipated onset of task failure could be accompanied by unexpected fatigue-related impairments to neuromuscular performance and a potential increase in injury risk. The experimenter noted that some participants expressed disappointment following their performance in the IIF80 trial, suggesting that they perceived the task to be more difficult than their previous experiences in the IIF60 familiarisation and assessment trials (as indicated by the higher CR-10 responses at the beginning of the IIF). In these instances, the participants appeared to attribute the cause of the shorter duration IIF80 to a deficiency in their own performance as opposed to acknowledging that the trial was being performed at a higher exercise intensity. It is impossible to determine whether or not the inaccurate PTD responses at termination of IIF80 imply an ineffective pacing mechanism or represent an under-reporting of values in an attempt to appear consistent with previous endeavours (Lewthwaite 1990).

The variations in intensity and duration between the two trials will have subjected the participants to different physiological and psychological demands. As such, the resulting afferent cues used to formulate perceptions of exertion and end-point may also have differed substantially. Golgi tendon activity has been proposed as a primary mechanism contributing to perceived exertion (Mihevic, 1981). However, an increase in muscle force is accompanied by a concomitant increase in a number of other variables that may impact upon perception of exertion, including blood lactate, heart rate and skin temperature (Temfemo et al., 2011). The significantly longer duration of IIF60 (27.2 ± 22.1 sets) in relation to IIF80 (6.3 ± 2.9 sets) will have potentially exposed participants to prolonged sensations of discomfort resulting from anaerobic metabolism. Elevated muscle lactate concentrations result in an increase in metabolic acidosis that stimulates nociceptors, resulting in sensations of pain in the involved muscle (Mihevic, 1981). It is postulated that sensory feedback of this nature may act as a protective mechanism that causes the individual to reduce work-rate or cease exercise in order to prevent damage to bodily structures (Hampson et al., 2001). In this instance, increased discomfort in response to elevated muscle acidity may have prompted a higher CR-10 or PTD response, consequently resulting in an underestimation of capabilities during the IIF60 trial. Whilst an underestimation of TD may potentially lead to a sub-optimal performance, it is arguably favourable to an overestimation of capabilities that could result in the unanticipated onset of fatigue and an associated potential risk of injury, as suggested by the PTD responses during the IIF80 trial.

Both IIF trials induced fatigue, as characterised by significant decreases in pre- to post-IIF PF and RFD. Interestingly, the significantly greater reductions in PF observed subsequent to the lower intensity IIF task were commensurate with those reported in the previous study detailed in Chapter 4. In contrast, volitional EMD performance was unaffected by fatigue. Estimates of magnetically-evoked neuromuscular performance were included in the current study with the aim of providing an indication of the relative contributions of central and peripheral fatigue to the termination of the IIF task. Analysis of evoked performance revealed a potentiated P_TF_E response following both IIF trials, but to a significantly greater extent following IIF80 (pre- to post-IIF increases of 83.5% and 120.9% for IIF60 and IIF80, respectively). Potentiated responses were also evident for RFD_E and EMD_E. Increasing intensity during volitional isometric muscle actions has been shown to produce greater potentiation of evoked twitch responses (Miyamoto et al., 2011). A potentiation of evoked responses following muscle fatiguing exercise may provide an indication of a 'reserve capacity' of unused motor units that could be recruited in an emergency situation such as threat of injury (Minshull et al., 2007). Considering the fatiguing nature of the IIF tasks in the current study, it is pertinent to acknowledge that mechanisms of fatigue and post-activation potentiation have been shown to coexist in skeletal muscle (Rassier and MacIntosh, 2000). The extent to which P_TF_E is suppressed by fatigue or enhanced by potentiation depends on the number and type of muscle fibres recruited during the preceding activity (Miyamoto et al., 2011). Fast type II fibres have previously demonstrated increased potentiation in comparison to type I fibres, but are also more susceptible to fatigue (Hamada et al., 2003). In accordance with the size principle of motor unit recruitment (Henneman, 1985), the greater amount of larger type II motor units likely to have been employed to perform the higher intensity IIF80 trial may have contributed to the greater potentiation of P_TF_E in comparison to IIF60. As previously highlighted, evidence of fatigue due to the IIF trials is provided by reductions in pre- to post-IIF volitional PF measures. However, due to the increased twitch response subsequent to both IIF trials, it is not possible to quantify the extent to which fatigue suppressed any potentiation effect on P_TF_E, and thus enable any estimation of the relative contributions of central and peripheral fatigue. It is important to address that the group mean body mass index values were situated in the overweight category (>26), and could indicate greater levels of body fat in some individuals that may have reduced the capability to achieve supra-maximal responses during magnetically-evoked stimulation (Tomazin et al., 2011). As a result, supra-maximal stimulation was attempted but could not be achieved in a number of participants, limiting the number of data sets available for analysis.

6.6. CONCLUSIONS

This study revealed that the CR-10 responses recorded during the initial stages of IIF80 were significantly higher than the corresponding values for IIF60, thus reflecting the 20% differential between target forces. However, visual inspection of the scatterplots revealed an apparent curvilinear trend in perceptual responses throughout the IIF60 trial that contrasts with much of the previously published research and with the findings of the previous study (detailed in Chapter 5). Whilst existing literature promotes a utility for RPE as a regulator of pacing strategies and predictor of running or cycling performance, the negatively accelerating curvilinear response during IIF60 would suggest an underestimation of capabilities. Although the perceptual responses during IIF80 exhibited a linear relationship with CTD, the PTD values provided an overestimation of capabilities, with a group mean response of 89.3% at the equivalent point of 100% CTD. These findings question the precise role of self-perception as a regulator of work-rate during intermittent isometric exercise tasks, and highlight a need for further investigation before concluding its utility during novel and intermittent exercise.

The second stage of this current investigation (as described in Chapter 7) was designed to provide a potentially greater disruption to perceptual mechanisms by incorporating a bout of eccentric muscle damaging exercise. This type of disturbance to neuromuscular function mirrors the introduction of unaccustomed exercise during a resistance training or injury rehabilitation programme. In these scenarios, sensory cues may be influenced by the presence of EIMD as a carry-over effect from prior exercise. This will, therefore, provide an ecologically valid method of disrupting the neuromuscular system and will enable further investigation into the relationship between self-perception and TD that might also be applicable to patient populations.

Chapter 7:
Effect of exercise-induced muscle damage on perceived exertion and task duration during an intermittent isometric fatigue task

CHAPTER 7: EFFECT OF EXERCISE-INDUCED MUSCLE DAMAGE ON PERCEIVED EXERTION AND TASK DURATION DURING AN INTERMITTENT ISOMETRIC FATIGUE TASK

7.1. ABSTRACT

The aim of this study was to examine the effects of exercise-induced muscle damage (EIMD) upon the relationship between task duration and two perceptual assessment paradigms (perceived exertion; perceived task duration) during an intermittent isometric fatigue trial (IIF). Eighteen university level male rugby players were randomly assigned to perform either an eccentric muscle damaging protocol (EIMD group) or a control condition (CON) comprising of rest of equivalent duration to the EIMD intervention. Participants performed IIFs at 60% baseline peak force 1hr pre- (IIF1) and 24 hours post-condition (IIF2). A two-way ANOVA revealed significantly greater perceived soreness in the EIMD group on the second assessment day compared to the CON group ($F_{[1,16]} = 30.7$; $p<0.001$). Although analyses revealed perceived exertion (CR-10) responses during IIF2 to be significantly higher than the corresponding values for IIF1 across the first three sets of the trial ($F_{[1,16]} = 6.5$; $p<0.05$), there were no significant effects for condition. In addition, EIMD was revealed to have had no effect on CR-10 or perceived task duration (PTD) responses during IIF2, suggesting that any disruptions as a consequence of increased muscle soreness did not impact upon the ability of the perceptual scales to act as a predictor of task duration. However, visual inspection of the data revealed curvilinear patterns of perceptual response in both IIF trials, thus questioning the efficacy of the two paradigms of self-perception (RPE; PTD) to act as predictors of task duration in isolated muscle exercise.

7.2. INTRODUCTION

The previous investigation (Chapter 6) discovered that participants' RPE responses (utilising a CR-10 scale) successfully discriminated between two IIF tasks involving a 20% differential in exercise intensity. Considering that RPE has been proposed as integral in the regulation of exercise (Tucker and Noakes, 2009), the detection of a 20% work intensity differential should theoretically have provided the basis from which the participants could make accurate judgements concerning TD and exercise capabilities. However, contrary to the previous findings (outlined in Chapter 5), both CR-10 and perceived completed task duration (PTD) displayed a negatively accelerating curvilinear trend during an IIF60, suggesting an underestimation of exercise capabilities. In an unsupervised exercise environment, elevated perceived demands during the early stages of an exercise bout may prompt the premature cessation of the task, resulting in a sub-optimal performance. In contrast, the perceptual responses during IIF80 exhibited a linear relationship with the percentage of completed task duration (CTD). However, the predictive capacity of PTD is questionable, due to group mean ratings of 89.3% at the equivalent point of 100% CTD. This finding suggests an overestimation of performance capabilities, with participants reaching the point of task failure sooner than anticipated.

The second stage of the investigation was to progressively increase the level of disruption to the participants by incorporating a bout of eccentric muscle damaging exercise. An incidence of EIMD typically occurs as a consequence of performing a bout of unaccustomed eccentric exercise, or exercise of a considerably increased volume and/or intensity (McHugh et al., 1999; Byrne et al., 2004). Examples of such scenarios could include an athlete returning to pre-season training following a period of relative inactivity, or a patient re-introducing unaccustomed dynamic exercise during rehabilitation from injury. Indeed, EIMD is evident following running (Eston et al., 1995; Howatson and Milak, 2009), plyometrics (Tofas et al., 2008; Twist et al., 2008) and resistance training (Paul et al., 1989; Yamamoto et al., 2008), all of which are incorporated into rehabilitation programmes for lower limb injuries (van Grinsven et al., 2010; Bailey et al., 2003) and in pre-season training programmes for multi-sprint sports (Burger and Burger, 2006; Corcoran and Bird, 2009; Holmberg, 2010). An acute bout of eccentric muscle damaging exercise has been shown to provoke substantial reductions in strength performance (Rinard et al., 2000; Byrne et al., 2001; Brown et al., 2010; Minshull et al., 2012), with associated symptoms of muscle soreness that typically peak 24-48 hours following the activity (Marginson et al., 2005; Twist and Eston, 2005; Torres et al., 2010; Minshull et al., 2012). The combination of reduced force production capability and localised pain may disrupt perceptual acuity, and subsequently impact upon pacing capabilities. For example, previous research has reported reduced proprioception subsequent to EIMD, with participants displaying a tendency to overestimate their level of force production (Saxton et al., 1995; Proske et al., 2004). A further issue of potential concern is that whilst perceived soreness may provide a sensory cue to minimise subsequent exercise stress and limit exposure to high injury-risk scenarios, it does not necessarily provide an accurate reflection of performance capabilities. Reductions in strength and power occur prior to the onset of soreness, and soreness symptoms can begin to dissipate before neuromuscular capabilities are fully restored (Byrne et al., 2004).

In addition to the impairment to neuromuscular performance and proprioceptive capabilities resulting from EIMD, disruption to sensory afferents may also be evident. For example, it is postulated that the onset of inflammation results in heightened sensitivity of group III and IV afferents, leading to increased sensations of pain that may inhibit muscle performance (Rice and McNair, 2009). This may lead to elevated levels of RPE during subsequent exercise (Davies et al., 2008) and consequently impact upon self-perception to act as a predictor of TD during exercise tasks. However, initial research exploring the impact of EIMD upon RPE and TD suggests there is a limited effect. Davies et al. (2009) recruited participants to perform a constant load cycle task to exhaustion both prior to and 48 hours subsequent to a muscle damaging protocol consisting of 100 squats with an external load of 70% body weight. Whilst exercise duration was significantly shorter and RPE was significantly elevated following muscle damage, the linear relationship between RPE and TD was unchanged from the pre-EIMD cycling trial. Marcora and Bosio (2007) conducted an investigation into the effects of EIMD on running performance, whereby participants were randomly assigned to an EIMD condition (consisting of 100 drop jumps) or control condition, and performed 30-minute time-trials prior to and 48 hours subsequent to the assigned condition. Whilst the EIMD condition provoked a 4% reduction in distance covered, no significant difference in RPE was observed, suggesting that participants perceived a similar level of exertion despite performing less work. In addition, the linear increase in RPE over time in all trials was consistent with other reported findings (Noakes, 2004; Eston et al., 2007; Crewe et al., 2008) and led the authors to conclude that EIMD did not impact upon the adopted pacing strategy (Marcora and Bosio, 2007). These findings provide some evidence to suggest that individuals are able to interpret the various altered sensory cues resulting from a bout of EIMD and make accurate judgments pertaining to levels of exertion, thus preserving the capability of RPE to act as a predictor of TD. However, the impact of EIMD on the relationship between effort perception and TD has yet to be explored in intermittent isometric exercise.

If judgements concerning perceived exertion and perceived task duration are affected by EIMD, then this will have implications for exercise pacing capabilities for athletes returning to activity following a bout of inactivity, and for patients being introduced to novel exercise modes during rehabilitation. The aim of this current study was, therefore, to examine the effects of EIMD upon the relationship between TD and two assessment paradigms (RPE; PTD).

7.3. METHODS

7.3.1. Participants

Eighteen university level male team rugby players (as detailed in Chapter 6.2.1) gave their written informed consent to participate in the study and were randomly assigned to either an EIMD group (n = 9; age 20.3 ± 2.3 years; height 174.0 ± 5.3cm; body mass 81.0 ± 11.7kg) or control group (n = 9; age 20.8 ± 1.5 years; height 179.6 ± 5.7cm; body mass 84.8 ± 11.5kg). The participant sample had also been utilised in the previous study (Chapter 6), having undertaken IIF60 and IIF80 trials as part of the previous study protocol. The data from the IIF60 trial from this previous protocol was utilised within the current study. All participants were asymptomatic of injury and were instructed to abstain from strenuous physical activity for the 24 hours preceding each testing session. Assessment protocols were approved by the Nottingham Trent University Ethical Committee for Human Testing. Sample participant information, consent form and health screen are included in Appendix D.

7.3.2. Experimental procedures and design

This was a mixed-model repeated measures design. Participants were required to attend the laboratory on a total of three occasions. The first occasion involved familiarisation and accommodation to rapid maximum voluntary muscle activation (MVMA) of the quadriceps, and perceptual measures. Also included was an exposure to the intermittent isometric fatigue task (IIF), whereby participants completed an entire IIF at 60% baseline peak force (PF), through to termination. This familiarisation session was incorporated to provide an exposure to and knowledge of the IIF and perceptual measures, and to minimise any learning effects in subsequent testing sessions.

The two remaining laboratory visits served as assessment sessions, with the first assessment session performed 48 hours subsequent to familiarisation. Fingertip blood samples and perceived soreness (described in section 7.2.7.2) were obtained at the beginning of each session. Following a standardised warm-up of five minutes cycle ergometry performed at 90 W, and an additional five minutes of stretching of the involved musculature, participants were secured in a seated position on a custom built dynamometer in accordance with the specifications outlined in Chapter 4.2.2. Estimates of evoked and volitional neuromuscular performance were obtained in order to establish baseline values. Participants were then required to perform an IIF at an intensity of 60% baseline PF (procedure as previously described in Chapter 6.2.2). Estimates of magnetically evoked and volitional neuromuscular performance were again obtained immediately after the IIF. Each participant was then randomly assigned to perform either an eccentric muscle damaging protocol (EIMD group) (protocol detailed in section 7.2.6) or a control condition comprising of rest of equivalent duration to the EIMD intervention. Assessment session two was performed 24 hours subsequent to the cessation of the EIMD or control tasks (± 1 hour), and required participants to perform one IIF at an intensity of 60% baseline PF (calculated from PF values obtained during session one). Estimates of static volitional neuromuscular performance were again obtained both prior to and immediately following the IIF.

7.3.3. Intermittent isometric fatigue task

The IIF protocol was performed in accordance with the description detailed in Chapter 4.2.3. Participants were 'blinded' to the precise magnitude of the target force

(60% baseline PF), but were able to observe in real-time how their efforts were matching the target line.

7.3.4. Perceptual measures

Measures of perceived exertion (CR-10) and perceived percentage of completed task duration (PTD) were recorded during each IIF inter-set rest period in accordance with the methods outlined in Chapter 4.2.4. Presentation of the scales was randomised in order to minimise any influence of the order on the participants' current perception.

7.3.5. Assessment of neuromuscular performance

Estimates of volitional and evoked neuromuscular performance were obtained and calculated in accordance with the procedures detailed in Chapter 4.2.5 and Chapter 6.2.5, respectively. Supra-maximal stimulation was not obtainable in all cases. As such, evoked neuromuscular performance data is presented from 14 participants (CON: n = 8; EIMD: n = 6). Furthermore, unforeseen technical issues hindered the collection of EMG data, and thus limited the calculation of EMD in some cases. EMD_{VL} and EMD_{VLE} data is presented from 11 participants (CON: n = 5; EIMD: n = 6).

7.3.6. Exercise induced muscle damage

The eccentric muscle damaging protocol was adapted from those utilised by Byrne et al. (2001) and Minshull et al. (2012). Pilot testing revealed that this protocol provoked significant reductions in PF (~30%), and provided a substantial muscle-damage response commensurate with the previous research. The protocol consisted of a warm up (5 submaximal and 5 maximal eccentric activations) followed by 10 sets (each separated by 2 minutes) of 10 repetitions of maximal eccentric activations of the knee extensors on an isokinetic dynamometer (Biodex, New York, USA). Each eccentric activation was performed at 60 $deg \cdot s^{-1}$ through a movement range of 10º to 90º of knee flexion (0º = full extension) and was followed by a passive return to the start position that was performed by the experimenter. Participants were able to observe their efforts in real time via a computer monitor, and verbal encouragement was provided to ensure that maximal effort was produced throughout.

7.3.7. Indirect markers of muscle damage

Prior to testing on both assessment sessions, subjective assessments of soreness of the involved knee extensors and fingertip blood samples for analysis of creatine kinase (CK) concentration were obtained.

7.3.7.1. Perceived soreness (visual analog scale)

Participants were required to stretch and actively extend the knee of their involved limb and rate their soreness on a 10cm visual analog scale (adapted from Minshull et al., 2012). The statements read: ‘my muscles don’t feel sore at all’ and ‘my muscles feel so sore that I don’t want to move them’, which corresponded to numerical ratings of 0 and 10, respectively, and that were shielded from the participants.

7.3.7.2. Creatine kinase (CK)

Blood samples were obtained via fingertip capillary puncture. A fingertip was cleaned with a sterile alcohol swab and allowed to dry. Capillary puncture was performed with a safety lancet and a sample of fresh blood was collected in a 500 µl microvette. Serum was separated from the blood cells by centrifugation at 13,000 rpm for 15 minutes and frozen at -80°C until analysis. Each sample was analysed in duplicate via an ABX Pentra 400 system (Horiba Instruments Inc., Irvine CA, USA), with the average value of the two measures used for subsequent statistical analysis.

7.3.8. Statistical analysis

All statistical analyses were performed using PASW v18.0 (SPSS Inc. Chicago, Il, USA).

Indirect markers of muscle damage (perceived soreness and CK concentrations) were assessed by separate two (time: day one; day two) by two (condition: EIMD; CON) mixed-model ANOVAs with repeated measures on first factor. A two (trial: IIF1; IIF2) by two (condition: EIMD; CON) mixed-model ANOVA with repeated measures on first factor was used to explore differences in IIF trial duration. Log transformations (log10) were applied where appropriate to satisfy assumptions of normality. Separate two (trial: IIF1; IIF2) by two (condition: EIMD; CON) mixed-model ANOVAs were used to analyse effects of the muscle damage intervention on baseline PF and P_TF_E data, in order to ascertain whether there were any carry-over effects. Effects of the IIF on each index of neuromuscular performance were evaluated by using separate two (trial: IIF1; IIF2) by two (time: pre; post) by two (condition: EIMD; CON) mixed-factorial ANOVAs. Differences in CR-10 measures over the first three sets of the IIF1 and IIF2 trial were analysed using a two (trial: IIF1; IIF2) by three (sets: 1; 2; 3) by two (condition: EIMD; CON) mixed-model ANOVA. Perceptual measures were also obtained at 10% intervals of the completed task duration (CTD), with CR-10 and PTD scores at 10% to 100% of the IIF task subsequently used for analysis. For those individuals whose scores did not fall on a 10% interval, a cubic spline function enabled interpolation of a value that was subsequently used for analysis (Keele, 2008). Changes in CR-10 and PTD over the duration of the IIF tasks (measures obtained at 10% intervals throughout the relative duration of the IIF, from 10% to 100% of the IIF) under each exercise intensity were analysed using separate two (trial: IIF1; IIF2) by ten (time: 10%; 20%; 30%; 40%; 50%; 60%; 70%; 80%; 90%; 100%) by two (condition: EIMD; CON) mixed factorial ANOVAs. Greenhouse-Geisser corrections were applied where assumptions of sphericity were violated, as indicated by $_{GG}$. Pearson product-moment correlation coefficients were used to explore the relationships between group mean perceptual responses (CR-10 and PTD) with the percentage of completed task duration (CTD) for the EIMD and CON groups during each trial (IIF1 and IIF2). All data were analysed using standard descriptive statistics (mean ± SD), and statistical significance was accepted at $p<0.05$.

7.4. RESULTS

7.4.1. Effects of eccentric muscle damaging protocol

Group mean data for baseline measures from assessment day 1 and assessment day 2 are presented in Table 7.1. A significant interaction associated with the two-way ANOVA for perceived soreness ($F_{[1,16]} = 30.7$; $p<0.001$) revealed a significantly greater soreness values in the EIMD group on the second assessment day compared to the CON group (increases of 471.1% vs. 8.6% for EIMD and CON groups, respectively). Despite an apparently greater increase in the EIMD group data, no significant differences for CK concentrations were found between conditions (reverse log transformed values presented in Table 7.1). A significant interaction associated with the two-way mixed-model ANOVA for IIF duration ($F_{[1,16]} = 12.9$; $p<0.01$) revealed that 49% fewer sets were performed in IIF2 versus IIF1 by the EIMD group (34 ± 24.3 sets vs. 17.3 ± 20.3 sets for IIF1 and IIF2, respectively), whilst the CON group performed 35.3% more sets during IIF1 versus IIF2 (20.4 ± 18.7 sets vs. 27.7 ± 19.7 sets for IIF1 and IIF2, respectively). Analysis of PF data revealed a significant main effect for day only ($F_{[1,16]} = 23.6$; $p<0.001$). No significant changes to P_TF_E were observed as a consequence of day or condition.

Table 7.1 Effects of muscle damaging protocol on baseline measures for assessment days 1 and 2 (group means ± SD)

Index			Day 1	Day 2	% change
Perceived soreness	(VAS)	CON	2.5 ± 1.2	2.7 ± 1.0	+8.6
		EIMD	1.0 ± 1.3	5.7 ± 2.1	+471.1*
CK	(U/L)	CON	499 ± 385	572 ± 416	+15.0
		EIMD	360 ± 185	631 ± 341	+83.2
IIF duration	(sets)	CON	20.4 ± 18.7	27.7 ± 19.7	+35.3
		EIMD	34.0 ± 24.3	17.3 ± 20.2	-49.0†
PF	(N)	CON	660.8 ± 142.3	620.9 ± 120.6	-6.0
		EIMD	576.0 ± 142.6	502.9 ± 147.8	-12.7
P_TF_E	(N)	CON	98.4 ± 24.2	100.4 ± 18.8	+1.7
		EIMD	94.6 ± 28.6	89.2 ± 19.0	-5.3

*Significant interaction between day and condition ($p<0.001$)
†Significant interaction between day and condition ($p<0.01$)

7.4.2. Perceptual measures

Initial CR-10 responses for the first three sets of IIF1 and IIF2 trials are illustrated in Figure 7.1. Analyses revealed a significant main effect for both trial ($F_{[1,16]}$ =6.5; $p<0.05$) and sets ($F_{[1.3,21.5\ GG]}$ =32.9; $p<0.001$) with CR-10 responses during IIF2 consistently higher than the corresponding values for IIF1 across the first three sets of the trial. There were no significant interaction effects.

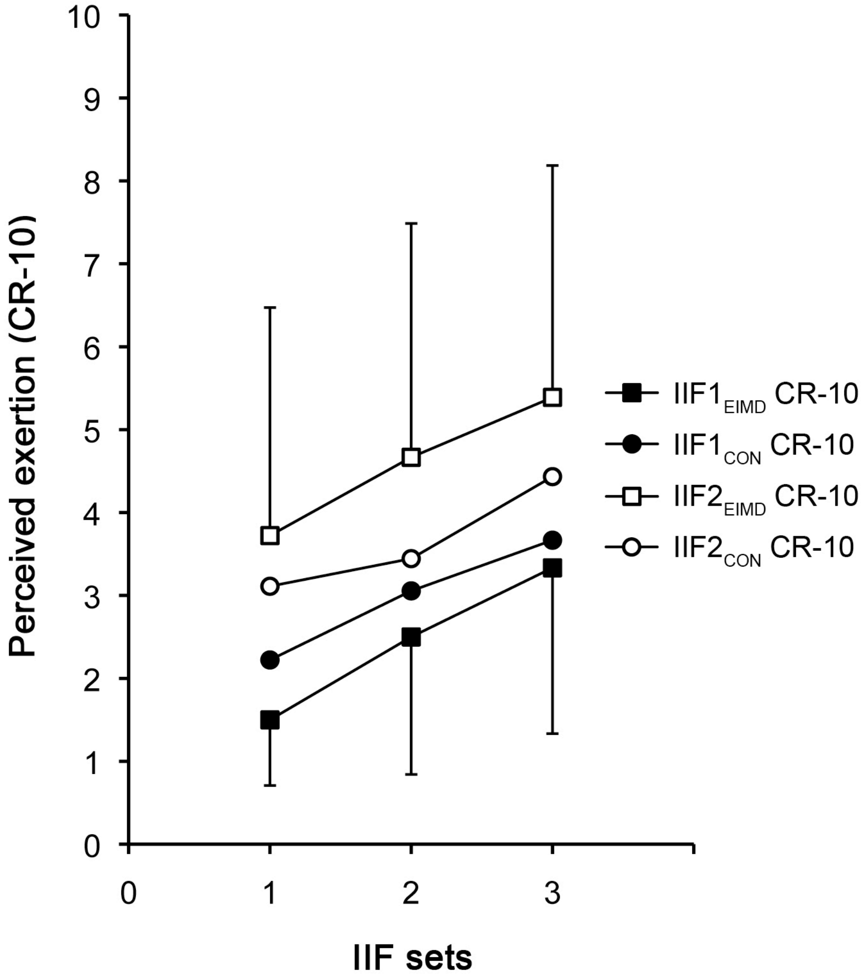

Figure 7.1 Initial CR-10 responses during IIF1 and IIF2 for EIMD and CON groups (group means ± SD)

Group mean data (± SD) and 95% CI for PTD responses during IIF1 and IIF2 are presented in Table 7.2. Changes in PTD across time for the IIF1 and IIF2 trials are illustrated in Figure 7.2a and Figure 7.2b for CON and EIMD, respectively. Analyses revealed a significant main effect for time only ($F_{[1.2,29.1\ GG]}$ =151.4; p<0.001). The interaction effect between trial and time approached significance but just exceeded the specified alpha level provided by the Greenhouse-Geisser correction (p=0.061). Pearson product-moment correlation coefficients revealed strong positive correlations between PTD and CTD for EIMD during both IIF1 (r=0.963; p<0.001) and IIF2 (r=0.973; p<0.001), and for CON during both IIF1 (r=0.986; p<0.001) and IIF2 (r=0.97; p<0.001).

Table 7.2 PTD responses (group means ± SD) and 95% CI for EIMD and CON groups during IIF1 and IIF2

	IIF1				IIF2			
	EIMD		CON		EIMD		CON	
% of CTD	Mean ± SD	95% CI	Mean ± SD	95% CI	Mean ± SD	95% CI	Mean ± SD	95% CI
10	23.3 ± 11.2	16.0-30.7	22.5 ± 15.1	12.6-32.3	39.3 ± 20.7	25.8-52.9	32.5 ± 13.7	23.5-41.5
20	42.4 ± 19.6	29.6-55.2	35.3 ± 19.9	22.3-48.4	51.0 ± 21.9	36.7-65.3	45.2 ± 14.9	35.5-55.0
30	54.3 ± 25.9	37.4-71.2	46.9 ± 20.9	33.2-60.5	62.1 ± 24.7	45.9-78.2	59.7 ± 16.8	48.8-70.7
40	66.6 ± 24.6	50.5-82.6	58.1 ± 19.1	45.1-71.1	69.3 ± 22.8	54.4-84.2	66.8 ± 16.9	55.8-77.8
50	75.0 ± 26.0	58.0-91.9	64.2 ± 19.	51.8-76.7	75.5 ± 19.6	62.7-88.3	77.9 ± 13.7	68.9-86.9
60	80.3 ± 21.4	66.3-94.3	76.0 ± 12.6	67.8-84.2	81.1 ± 17.3	69.8-92.4	81.3 ± 15.0	71.5-91.1
70	88.6 ± 12.5	80.4-96.7	83.5 ± 8.7	77.8-89.2	87.3 ± 13.0	78.8-95.8	87.0 ± 13.4	78.2-95.7
80	91.1 ± 10.8	84.0-98.2	90.3 ± 7.8	85.2-95.4	91.1 ± 9.7	84.8-97.4	90.5 ± 9.3	84.5-96.6
90	95.3 ± 6.3	91.2-99.4	93.6 ± 7.0	89.0-98.2	93.5 ± 6.6	89.1-97.8	96.1 ± 4.9	92.9-99.3
100	98.7 ± 1.9	97.4-99.9	97.9 ± 4.9	94.7-10.1	96.0 ± 5.3	92.5-99.5	98.9 ± 1.7	97.8-100.0

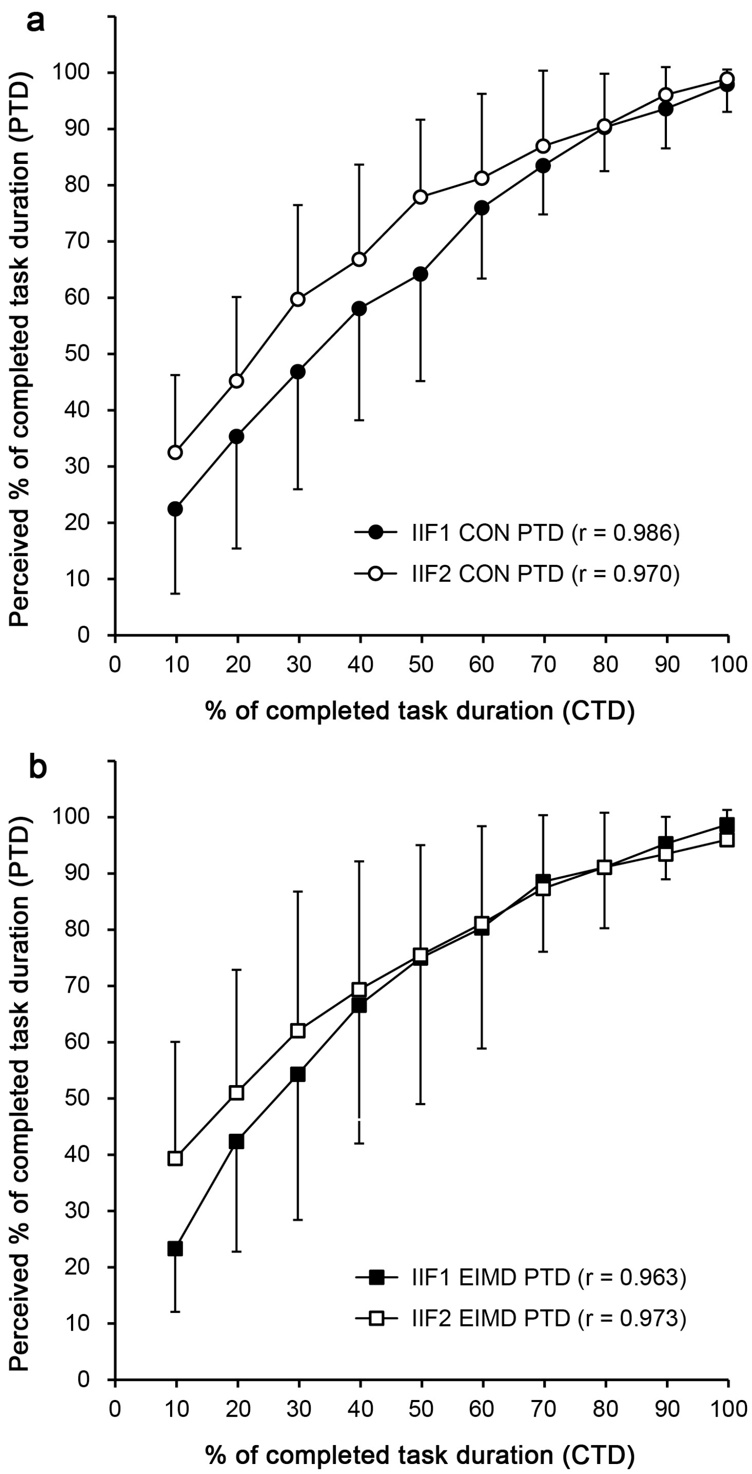

Figure 7.2 a) PTD responses during IIF1 and IIF2 for CON group (group means ± SD); b) PTD responses during IIF1 and IIF2 for EIMD group (group means ± SD)

Group mean (± SD) and 95% CI for CR-10 responses during IIF1 and IIF2 are presented in Table 7.3. Changes in CR-10 across time for the IIF1 and IIF2 trials are illustrated in Figure 7.3a and Figure 7.3b for CON and EIMD, respectively. Analyses revealed a significant main effect for time only ($F_{[1.9,30.4\ GG]}$ =111.8; p<0.001). Pearson product-moment correlation coefficients revealed strong positive correlations between CR-10 and CTD for EIMD during both IIF1 (r=0.953; p<0.001) and IIF2 (r=0.958; p<0.001), and for CON during both IIF1 (r=0.957; p<0.001) and IIF2 (r=0.954; p<0.001).

Table 7.3 CR-10 responses (group means ± SD) and 95% CI for EIMD and CON groups during IIF1 and IIF2

	IIF1				**IIF2**			
	EIMD		**CON**		**EIMD**		**CON**	
% of CTD	**Mean ± SD**	**95% CI**	**Mean ± SD**	**95% CI**	**Mean ± SD**	**95% CI**	**Mean ± SD**	**95% CI**
10	3.2 ± 1.3	2.4-4.0	3.2 ± 1.6	2.1-4.2	4.4 ± 1.9	3.2-5.7	3.8 ± 1.7	2.7-5.0
20	5.2 ± 1.9	4.0-6.5	4.4 ± 1.9	3.2-5.7	5.7 ± 2.0	4.4-7.0	5.1 ± 1.8	3.9-6.3
30	6.4 ± 2.4	4.9-8.0	5.8 ± 1.8	4.5-7.0	6.9 ± 2.3	5.4-8.3	6.5 ± 1.8	5.3-7.6
40	7.3 ± 2.2	5.9-8.8	6.9 ± 1.8	5.8-8.1	7.6 ± 2.0	6.3-8.9	7.6 ± 1.6	6.5-8.6
50	8.0 ± 2.2	6.6-9.4	7.8 ± 1.2	7.0-8.6	8.1 ± 1.7	7.0-9.2	8.2 ± 1.3	7.3-9.1
60	8.5 ± 1.9	7.3-9.7	8.4 ± 1.4	7.5-9.3	8.8 ± 1.2	8.1-9.6	8.6 ± 1.0	8.0-9.3
70	9.1 ± 1.1	8.4-9.7	8.9 ± 0.9	8.3-9.5	9.4 ± 0.6	9.0-9.8	9.1 ± 0.8	8.6-9.6
80	9.5 ± 0.8	9.0-10.0	9.3 ± 0.9	8.7-9.9	9.8 ± 0.3	9.5-10.0	9.5 ± 0.5	9.2-9.9
90	9.8 ± 0.4	9.6-10.1	9.5 ± 1.0	8.9-10.1	9.8 ± 0.4	9.6-10.1	9.6 ± 0.4	9.4-9.9
100	10.0 ± 0.0	n/a	9.7 ± 1.0	9.0-10.3	9.9 ± 0.3	9.7-10.1	10.0 ± 0.0	n/a

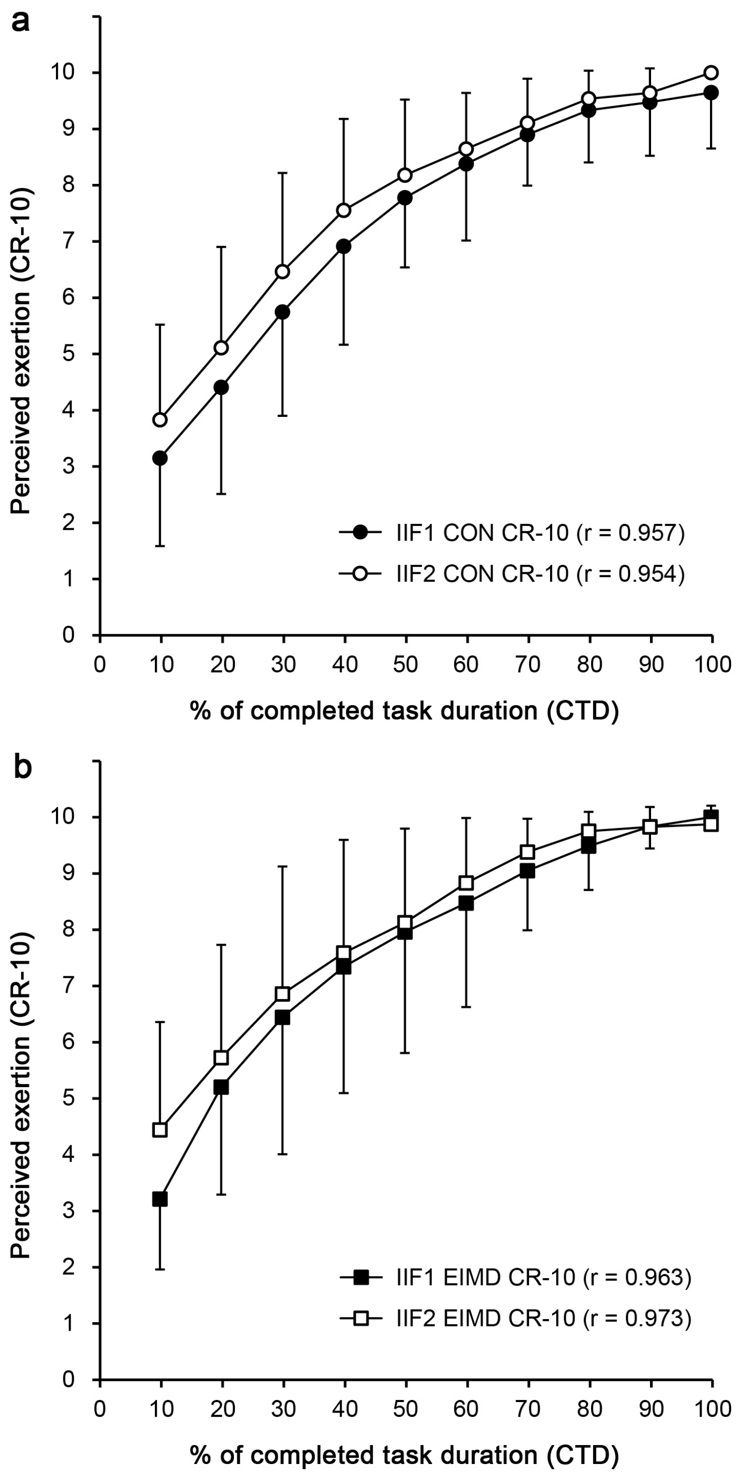

Figure 7.3 a) CR-10 responses during IIF1 and IIF2 for CON group (group means ± SD); b) CR-10 responses during IIF1 and IIF2 for EIMD group (group means ± SD)

7.4.3. Effects of the IIF intervention

7.4.3.1. Volitional neuromuscular performance

Group mean data for pre- and post-IIF indices of volitional neuromuscular performance are presented in Table 7.4. There were no significant three-way interactions (time by trial by condition). A significant interaction between trial and condition revealed a lower overall PF in the EIMD group for IIF2 ($F_{[1,16]}$ =7.7; p<0.05). A significant interaction between trial and time indicated that both IIF tasks led to reductions in PF, but to a greater extent following the IIF1 task compared to the IIF2 task ($F_{[1,16]}$ =9.5; p<0.01) (group mean pre- to post-IIF PF reductions of 16.3% and 9.4%, for IIF1 and IIF2, respectively). A significant main effect for time revealed that both IIF trials led to similar reductions in RFD ($F_{[1,16]}$ =8.4; p<0.01) that was also similar between conditions (combined group mean pre- to post-IIF RFD reductions of 20.6%). A main effect for condition revealed EMD_{VL} values to be significantly higher for the EIMD group versus CON ($F_{[1,9]}$ =8.8; p<0.05). No significant effects were observed for EMD_{VM}.

Table 7.4 Indices of volitional neuromuscular performance for IIF1 and IIF2 trials (group means ± SD)

Index			IIF1 Pre	IIF1 Post	IIF1 % change	IIF2 Pre	IIF2 Post	IIF2 % change
PF	(N)	CON	660.8 ± 142.3	536.3 ± 145.3	-18.8	620.9 ± 120.1	561.3 ± 128.5*†	-9.6
		EIMD	576.0 ± 142.6	496.8 ± 139.4	-13.7	502.9 ± 147.8	456.9 ± 133.8	-9.2
RFD	($N^{\cdot s^{-1}}$)	CON	4190 ± 1703	3574 ± 1646	-14.7	3803 ± 1539	3162 ± 1390	-16.9
		EIMD	3673 ± 1369	2684 ± 1267	-26.9	3696 ± 1162	2799 ± 1262	-24.3
EMD_{VL}	(ms)	CON	32.4 ± 5.3	32.2 ± 7.75	-0.6	31.8 ± 5.0	26.7 ± 3.8	-16.0
		EIMD	41.2 ± 5.9	35.3 ± 3.63	-14.3	39.0 ± 9.1	38.5 ± 5.2	-1.28
EMD_{VM}	(ms)	CON	30.8 ± 3.2	31.2 ± 4.2	+1.3	31.4 ± 4.8	32 ± 6.2	+1.9
		EIMD	36.3 ± 6.3	32.6 ± 3.0	-10.2	38.5 ± 12.2	31.7 ± 3.2	-17.7

*Significant interaction between trial and time (p<0.01)
†Significant interaction between trial and condition (p<0.05)

7.4.3.2. Evoked neuromuscular performance

Group mean data for pre- and post-IIF indices of evoked neuromuscular performance are presented in Table 7.5. A significant interaction between trial and condition revealed greater P_TF_E in the CON group for IIF2 ($F_{[1,12]}$ =5.9; p<0.05). Compared to baseline levels, both IIF tasks led to significant increases in P_TF_E in both the EIMD and CON groups ($F_{[1,12]}$ =18.1; p<0.001) (combined group mean pre- to post-IIF performance improvements of 29.1%). Pre- to post-IIF increases were similarly evident for RFD_E in both the EIMD and CON groups following both IIF trials ($F_{[1,12]}$ =44.3; p<0.001) (group mean pre- to post-IIF RFD performance improvements of 94.2%). Results for both EMD_{VLE} ($F_{[1,9]}$ =15; p<0.01) and EMD_{VME} ($F_{[1,12]}$ =5.8; p<0.05) revealed significant main effects for time only, with similar improvements pre- to post-IIF evident in both conditions (group mean pre- to post-IIF improvements of 9.8% and 4.6% for EMD_{VLE} and EMD_{VME}, respectively).

Table 7.5 Indices of evoked neuromuscular performance for IIF1 and IIF2 trials

Index			IIF1			IIF2		
			Pre	**Post**	**% change**	**Pre**	**Post**	**% change**
P_TF_E	(N)	CON	98.4 ± 24.2	117.0 ± 33.2	+18.9	100.4 ± 18.8	137.3 ± 34.4*	+36.7
		EIMD	94.6 ± 28.6	122.3 ± 34.2	+29.4	89.2 ± 19.0	117.2 ± 21.4	+31.3
RFD_E	($N^{.s-1}$)	CON	1419 ± 394	2434 ± 816	+71.5	1409 ± 285	2979 ± 1051	+111.3
		EIMD	1281 ± 364	2414 ± 887	+97.9	1294 ± 260	2539 ± 620	+96.1
EMD_{VLE}	(ms)	CON	15.8 ± 2.0	14.5 ± 0.8	-8.2	15.8 ± 1.7	14.3 ± 1.4	-9.5
		EIMD	16.4 ± 1.7	14.2 ± 1.6	-13.4	16.0 ± 1.1	14.7 ± 1.4	-8.1
EMD_{VME}	(ms)	CON	14.6 ± 1.7	14.3 ± 1.8	-2.0	14.4 ± 1.1	14.2 ± 1.5	-1.4
		EIMD	14.0 ± 0.9	13.2 ± 1.5	-5.7	14.3 ± 0.9	13.0 ± 1.0	-9.1

*Significant interaction between trial and condition (p<0.05)

7.5. DISCUSSION

The major finding from the current study is that EIMD did not impact upon the relationships between CTD and self-perception measures (CR-10 and PTD) during intermittent static muscle exercise. The eccentric muscle damaging protocol was sufficient to produce a significantly greater increase in perceived soreness (471.1% vs. 8.6% for EIMD and CON, respectively). However, whilst elevated CK levels are typically evident following intense exercise and are commonly used to provide an indication of muscle damage (Brancaccio et al., 2007), CK concentrations in the current study were not significantly different between conditions. This could be attributed to the high level of inter-individual variability of CK that has previously been reported to range between <100 U/L and 3000 U/L (Hartmann and Mester, 2000). In the context of the current investigation, the participants' self-perceived soreness is arguably of greater interest, as it confirms that the EIMD group experienced conscious sensations of pain and discomfort that were not encountered to the same extent by the CON group.

Comparison of the first three sets of each IIF indicated that group mean CR-10 responses during the early stages of the IIF2 trial were higher than the equivalent responses during IIF1 for both the EIMD and CON groups. This perceived increase in demand reflects the significant reduction in PF between the pre-IIF1 and pre-IIF2 baseline values (12.7% and 6% for the EIMD and CON groups, respectively). Previous investigation of force replication tasks performed in muscles symptomatic of EIMD has observed a tendency for participants to underestimate the required target force, and thus produce lower levels of muscle force than required (Saxton et al., 1995; Proske et al., 2004). The current findings would suggest that participants were able to interpret their reduced force production capabilities and greater relative task demands in the IIF2 trial (Figure 7.1). The volitional PF reductions experienced by the EIMD group (12.7%) were not significantly different to those present in the CON group (6%), suggesting that there may have been some form of carry-over effect from the IIF trials completed on the previous day. When examining typical responses of the knee extensors to muscle damaging protocols, the baseline PF reductions experienced by the EIMD group were consistent with some previously reported findings (Marcora and Bosio, 2007), but lower in comparison to other research (Byrne and Eston, 2001; Paschalis et al., 2007; Trombold et al., 2011). No significant reductions in evoked P_TF_E were found between the IIF1 and IIF2 trials. This may indicate a centrally-mediated reduction in volitional performance for both CON and EIMD groups, potentially attributed to inhibition resulting from activity of group III and IV afferents in response to muscle soreness (Racinais et al., 2008). Moreover, a significantly greater increase in overall P_TF_E (combined pre- and post-IIF values) was evident for the CON group compared to the EIMD group for IIF2. This finding may point towards additional peripheral impairments experienced in the EIMD group.

While the eccentric exercise protocol provoked considerable changes to IIF duration (a 49% reduction for EIMD vs. a 35.3% increase for CON), no significant differences in CR-10 or PTD response could be attributed to the EIMD condition. However, an apparent curvilinear relationship with CTD was evident for both paradigms of effort sense in all trials. As previously highlighted, the elevated responses in the early stages of both IIF trials may represent an under-estimation of capabilities that could translate to a sub-optimal performance or early cessation of exercise. In Chapter 6 it was hypothesised that the extended duration of IIF60 in comparison to IIF80 may have subjected participants to prolonged sensations of discomfort resulting from stimulation of nociceptors due elevated metabolic acidosis (Mihevic, 1981). Indeed, this may be exacerbated under conditions of EIMD due to an increased rate of glycogen utilisation as a consequence of greater recruitment of fast type II fibres (Gleeson et al., 1998). Pain sensations may consequently act as a protective mechanism to influence the individual to reduce work-rate (Hampson et al., 2001), and in the context of the current study may, therefore, have prompted selection of relatively higher perceptual ratings. Although the $IIF2_{EIMD}$ trial was substantially shorter in comparison to IIF2$_{CON}$, the activation of nociceptors in response to muscle damage (Racinais et al., 2008) may have acted in a similar protective capacity, and provoked elevated CR-10 and PTD responses.

It is possible that EIMD-related changes to glycogen utilisation may have been a cause of the significantly shorter duration of the IIF2$_{EIMD}$ trial. An acute bout of muscle damage may inhibit glycogen synthesis (O'Reilly et al., 1987). In addition, although fast type II fibres may be more susceptible to EIMD (Brockett et al., 2002), there may be additional damage to some type I oxidative fibres that results in an increased demand placed upon glycolytic energy production (Tee et al., 2007). This may in turn have impacted upon the perceptual responses in relation to CTD. The linear relationship between RPE and TD during other exercise modalities has prompted the theory that a subconscious glycogen-based signal is used to inform RPE during exercise (Noakes, 2004). It is postulated that if exercise was solely limited by the depletion of energy substrates, then RPE responses in these fixed work-rate tasks would be characterised by a rapid increase towards the end of the exercise bout when glycogen stores were depleted to critically low levels (Tucker, 2009). Instead, RPE values have previously been shown to demonstrate a progressive increase as glycogen levels are gradually depleted (Noakes, 2004). Despite the substantially reduced IIF2$_{EIMD}$ duration and potential stresses on glycogen synthesis and utilisation following muscle damage, the group mean perceptual responses between the EIMD and CON groups were similar. The lack of differences in perceptual response between the EIMD and CON groups across the duration of the IIF tasks would suggest that participants were able to interpret any changes in afferent feedback resulting from muscle damage and any potential carry-over effects from the previous IIF, and form their perceptual responses accordingly. However, this apparent recognition of the relatively increased demands of IIF2 did not improve the capacity of the PTD and CR-10 scales to predict CTD.

7.6. CONCLUSIONS

Whilst the effects of EIMD upon the relationship between self-perception and TD appear to be negligible, it is difficult to properly ascertain the precise impact due to the unanticipated carry-over effects of the preceding IIF task. CR-10 responses were higher during the early stages of IIF2 in comparison to the corresponding stages of IIF1, thus reflecting the greater demands of the IIF2 task as a consequence of the impaired force production capabilities. This would suggest that disruptions to the involved musculature resulting from the preceding day's activity were interpreted by the participants and reflected in an elevated perceptual response. However, this altered RPE did not contribute to an accurate prediction of TD, as visual inspection of the scatterplots revealed curvilinear patterns of perceptual response in both the IIF1 and IIF2 trials (similar to those reported in Chapter 6), which reflect an underestimation of capabilities that could potentially translate to a sub-optimal performance. Furthermore, the suggestion of a trend towards elevated PTD responses at the beginning of IIF2 may also point to an underestimation of capabilities, with participants perceiving that they had completed >30% of the IIF task, when in reality they had only completed 10% of the total duration.

The combined results from an asymptomatic population as described in Chapters 6 and 7 appear to suggest that the self-perception responses share an apparent curvilinear relationship with TD during an IIF performed at 60% PF, and thus question the ability of the two paradigms of self-perception (RPE; PTD) to act as predictors of TD in isolated muscle exercise. Based on these findings, these perceptual scales would appear to have limited utility in a clinical population, where the combination of injury, surgery and de-conditioning may further increase inter-individual variation in response.

Chapter 8:

General Discussion and conclusions

CHAPTER 8: GENERAL DISCUSSION AND CONCLUSIONS

8.1. INTRODUCTION

The research described in this thesis has examined if self-perception of physical capabilities can be used to provide an accurate indication of objective performance outcomes. This was undertaken with the aim of determining the utility of perceptual scales can be used to assist with the self-regulation of isolated, intermittent muscle exercise such as that performed during resistance training regimes and also during structured rehabilitation following ACL-reconstructive surgery. The present chapter will discuss the main findings of this research with regard to the implications for optimising performance and preventing re-injury. It will then review the methods adopted and identify potential improvements that could be applied to further investigations in this area, and provide indications as to the possible direction of this future research. Finally, this general discussion will consider potential applications for the present findings, with reference to the scope and limitations of the research.

8.2. REVIEW OF FINDINGS

The general proposition that RPE rises linearly during running and cycling has been addressed in detail in Chapter 2. Much of the research reviewed examined the performance of endurance-trained participants during continuous running and cycling exercise. However, the findings from these sporting activities undertaken by asymptomatic athletes have limited application to the intermittent and isolated modes of exercise that characterise resistance training and early-stage post-operative ACL rehabilitation. It was therefore necessary to explore the pattern of perceptual responses in an appropriate context that could have implications for a clinical environment. In addition, ACL-reconstructed patients face the additional challenge of progressing their rehabilitation at an optimal rate without jeopardising the integrity of the replacement graft (Marumo et al., 2005). Although physical therapy is an integral component of the recovery process, often the limited available contact time with a clinician dictates that a substantial amount of exercise performance and progression is undertaken in the absence of specialist supervision following advice from the physiotherapist (Coppola and Collins, 2009). A positive functional outcome has to be achieved in the presence of a considerable perturbation to the knee joint as a consequence of the injury and required surgery (Forster and Forster, 2005; Krogsgaard et al., 2011). This disturbance may subsequently produce novel sensations to which the patient is unaccustomed, thus providing a potential disadvantage when attempting to accurately judge the progress of rehabilitative exercise. Chapters 3 to 7 reported a series of empirical studies that were designed to explore the relationships between self-perceived and objective aspects of knee-joint performance. The aims and key findings from these studies are presented in Table 8.1

Table 8.1 Aims and key findings of empirical chapters

Study	Aims and Key Findings
Study 1: Relationships between self-perceived knee function and indices of musculoskeletal performance in an ACL-reconstructed population (Chapter 3)	**Aims** • Explore the relationships between self-perceived measures of knee function and objective indices of musculoskeletal performance in an ACL-reconstructed population during various stages of post-operative rehabilitation, ranging from pre-surgery through to an anticipated completion of rehabilitation at 48 weeks post-surgery. **Key Findings** • Analyses revealed a lack of significant correlations between self-perceived and objective measures throughout the early to intermediate stages (pre-surgery to 24 weeks) following surgery. • Relationships between self-perceived and objective knee function became stronger in the latter stages of rehabilitation (48 weeks).
Study 2: Reproducibility and reliability of two perceptual scales during an intermittent isometric fatigue task (Chapter 4)	**Aims** • Assess the reliability of two perceptual measurement scales during a novel intermittent isometric fatigue task (IIF): **i.** Measurement of perceived exertion using the category-ratio RPE scale (CR-10). **ii.** Measurement of perceived percentage of completed task duration (PTD) using a visual analog scale. **Key Findings** • Composite inter-day ICC scores suggested a good level of agreement between trials for both scales. • Composite V% values indicated greater intra-individual variability than reported in previous studies. V% of 33.1% was observed at 10% completed IIF duration, equating to 0.9 absolute units of measurement.
Study 3: Congruency and responsiveness of perceived exertion and task duration during an intermittent isometric fatigue task (Chapter 5)	**Aims** • Investigate the relationship between measures of self-perception (RPE; PTD) and completed task duration in an IIF • Evaluate the capability of two assessment paradigms (RPE; PTD to reflect a 10% change in IIF intensity. **Key Findings** • Visual inspection of the data revealed linear patterns of perceptual response in both IIF trials for both CR-10 and PTD scales. • CR-10 responses did not reflect the 10% differential in IIF intensity.
Study 4: Effect of a substantial variation in work intensity on perceived exertion and task duration during an intermittent isometric fatigue task (Chapter 6)	**Aims** • Evaluate the capability of two perceptual assessment paradigms (RPE; PTD) to reflect a 20% differential in IIF work intensity • Determine if the variation in target force impacts upon the relationship and pattern of perceptual response in relation to task duration. **Key Findings** • Initial CR-10 responses reflected 20% differential in IIF work intensity. • Curvilinear patterns of perceptual response evident in both IIF trials.
Study 5: Effect of exercise-induced muscle damage on perceived exertion and task duration during an intermittent isometric fatigue task (Chapter 7)	**Aims** • Examine the effects of exercise-induced muscle damage (EIMD) upon the relationship between task duration and two perceptual assessment paradigms (RPE; PTD) during an IIF **Key Findings** • EIMD was revealed to have had no effect on CR-10 or PTD responses. • Curvilinear patterns of perceptual response evident in both IIF trials.

Chapter 3 was a longitudinal study conducted over a 34-month period that examined a cohort of ACL-reconstructed patients as they completed a 48-week rehabilitation programme. This process involved monitoring the progression of important markers of objective musculoskeletal fitness alongside two measures of self-perceived knee function (PP and IKDC). The findings revealed patterns of change in objective measures that were generally characterised by an initial deterioration of performance in the injured limb following surgery, followed by gradual improvement over the course of the rehabilitation period. In particular, the greatest improvements in neuromuscular capabilities were observed between weeks 6 and 12, which corresponds with a progression in resistance exercise both in terms of increased intensity and range of motion (see Figure 2.2). Self-perceived knee function, however, typically provided a poor reflection of musculoskeletal performance. Indeed, it was only at week 48 that self-perceived measures (via IKDC response) began to provide any noticeable indication of the patients' objective capabilities. This may point to a possible latency period, whereby a patient's self-perceived function begins to reflect the objective capabilities subsequent to having 'tested' the knee during functional activities. The lack of any strong relationships between perceived and objective measures across the early to intermediate phases of rehabilitation could suggest the disparity is, in part, driven by patient confidence in their functional capabilities. Indeed, a lack of confidence following ACL reconstruction has been proposed as an explanation for extended absence from full activity (Webster et al., 2008). Considering that individuals with lower self-efficacy regarding performance of an exercise task have been observed to report higher RPE values (Hu et al., 2007), a lack of confidence in the reconstructed knee might, therefore, have implications for the utility of RPE in the self-regulation of exercise during rehabilitation. The relationships observed at 48 weeks may provide some justification for the use of PP and IKDC as indicators of knee function at the end stages of the rehabilitation. However, the discrepancy between self-reported and objective function questions the efficacy of PP and IKDC as tools for monitoring and regulating exercise progression throughout the early to intermediate post-operative phases of rehabilitation, and highlighted a need for further investigation into perceived capabilities during this period. Concurrent with recruitment and testing during this longitudinal study, a series of investigations (Chapters 4 to 7) explored two paradigms of self-perception (RPE; PTD) related to TD during isolated intermittent muscle exercise, such as that might be performed during the early to intermediate stages of rehabilitation.

Before relationships between self-perception and TD could be investigated, it was necessary to establish the efficacy and reliability of measurement scales used to provide estimates of RPE and PTD. Chapter 4 provided a justification for the selection of a CR-10 scale (Borg, 1998) and a visual analog scale to measure RPE and PTD, respectively. In addition, a level of test-retest reliability was established for both measures, with composite V% and ICC values providing an indication of the levels of intra-session variability and the degree of association for each of the perceptual scales. Significant ICCs (>0.82) were comparable to previously reported values obtained during isometric (Elfving et al., 1999) and isotonic resistance exercise (Day et al., 2004; McGuigan et al., 2004), whilst V% values (~22%) were slightly higher than those previously observed in isometric (Elfving et al., 1999) and isotonic resistance exercise (Day et al., 2004). Separate calculations of V% values for perceptual responses at each 10% interval of CTD enabled a more precise indication of the accuracy of the scales across the different stages of the IIF task. An inter-day variability in CR-10 response of 33.1% was evident at 10% of CTD, equating to 0.9 absolute measurement units on the CR-10 scale. Therefore, CR-10 responses at the beginning of an IIF task would have to exceed this margin in order to reflect any variation in exercise intensity. Having identified a level of reliability for the RPE and PTD measures, the validity of the scales could then be investigated with regard to establishing their utility in providing an accurate prediction of TD.

Chapter 5 explored the relationship that the two paradigms of self-perception (RPE; PTD) shared with percentage of completed task duration (CTD) during an IIF. This chapter also examined the effect of withholding information regarding a 10% differential in IIF target force, to test whether or not the change in intensity could be detected by participants and consequently reflected in their perceptual responses. An inaccurate perception of work intensity would potentially compromise a performer's ability to select an appropriate 'template RPE', and subsequently impact upon their judgements regarding the anticipated demands of the exercise task (Tucker, 2009). RPE and PTD were found to increase linearly in both the IIF60 and IIF70 tasks, thus supporting previous findings of a linear relationship between RPE and CTD in cycling and running activities (Horstman et al., 1979; Noakes 2004; Eston et al., 2007; Crewe et al., 2008). However, the 95% confidence intervals for RPE and PTD indicated a large variance in the group response, highlighting a need for caution before recommending the utility of the scales in predicting CTD during isolated muscle exercise. Furthermore, the lack of significant change in perceptual response as a consequence of the varied IIF intensity, coupled with the high inter-day variability in CR-10 response at 10% of CTD (33.1%; Chapter 4), led to the conclusion that the CR-10 scale did not provide sufficient sensitivity to detect a 10% differential in target force.

Given the novel and exploratory nature of the series of studies described in Chapters 4 to 7, it was not possible to routinely calculate the appropriate sample size necessary to avoid a Type II error. The practicalities of participant recruitment and retention, coupled with the availability and access to laboratory facilities, necessitated additional methods of improving the experimental design sensitivity. As such, participants for subsequent investigations (Chapters 6 and 7) were recruited from a similar population of competitive university level rugby players (as opposed to general team games players) in an attempt to increase the homogeneity of the sample, in addition to employing a larger IIF work intensity differential.

Chapter 6 developed the theme of the previous investigation by increasing the IIF target force differential to 20%. The results demonstrated that the CR-10 responses obtained during the first three sets of each IIF task did reflect the increase in intensity. However, in contrast to the previous study, the pattern of responses across the duration of IIF60 revealed a negatively accelerating growth curve, whereby a higher rate of increase in perceptual response is evident in the early stages of the exercise task. In this instance, the continuation of a linear trend based on the initial perceptual responses would predict an early cessation of the exercise task (for a theoretical example, see Figure 1.1b). In practical terms, the elevated perceptual responses during the first half of IIF60 represent an underestimation of capabilities, as the participants were able to continue the exercise task for substantially longer than expected. In an unsupervised environment, this misperception may prompt the premature termination of the exercise bout, and thus result in a sub-optimal performance. Conversely, whilst the group responses during IIF80 demonstrated a linear trend, PTD values of ~89% at 100% CTD suggested an unexpected onset of task failure due to an overestimation of capabilities. In an applied setting, a misjudgement of this nature would expose participants to unanticipated fatigue-related performance decrements, and might have associated implications for a potential increased risk of injury. The different patterns of response may be linked to the duration of the IIF tasks (27.2 ± 22.1 sets vs. 6.3 ± 2.9 sets for IIF60 and IIF80, respectively), whereby the extended duration of IIF60 may have caused prolonged sensations of discomfort resulting from the stimulation of nociceptors as a consequence of metabolic acidosis ((Mihevic, 1981), thus elevating the perceptual responses.

Chapter 7 provided the participants with a progressive increase in perturbation to the neuromuscular system in the form of an eccentric muscle damaging exercise protocol. The inclusion of a bout of EIMD was designed to mimic the exercise stresses caused by the re-introduction of dynamic exercise during the rehabilitation programme. Despite provoking significant changes to IIF duration, the EIMD group demonstrated no difference in perceptual response throughout the task. However, unforeseen carry-over effects of the preceding IIF task (as evidenced by impaired neuromuscular performance in the CON group) created difficulties in establishing the precise impact of EIMD. In addition, further evidence was provided for the curvilinear trend in the IIF60 trial described in Chapter 6. An observed trend in elevated PTD responses at the beginning of IIF2 revealed that participants perceived that they had completed >30% of the IIF task at an equivalent of only 10% CTD, thus suggesting an underestimation of capabilities. The combined findings from an asymptomatic population question the utility of RPE and PTD to act as predictors of TD in isolated muscle exercise, and would, therefore, suggest that the scales would have limited application in a clinical population.

8.3. IMPLICATIONS FOR PERFORMANCE

The collective findings from the research presented in this thesis question the efficacy of self-perception to provide an accurate reflection of various aspects of knee-joint performance. The combination of linear and curvilinear trends in CR-10 and PTD group responses questions the utility of these scales as accurate predictors of exhaustion time during intermittent isolated muscle exercise. Indeed, it can be argued that the existing evidence highlighting a linear relationship between RPE and TD in other exercise modalities is not wholly conclusive, given the range of methods of data analysis utilised in these previous studies (as detailed in Chapter 2). For example, the finding that RPE and ETL responses were unable to predict end-point (Garcin et al., 2004) conflicts with evidence purporting that RPE can provide an accurate prediction of exhaustion time during running and cycling (Horstman et al., 1979; Eston et al., 2007; Crewe et al., 2008).

Despite a lack of conclusive evidence to support the concept that RPE scales linearly with time, the current findings do not necessarily negate that self-perception fulfils some role in regulating exercise performance. Whilst a perfect linear relationship would represent an optimal prediction of exhaustion time, a negatively accelerating curvilinear relationship (as reported during IIF60 in Chapters 6 and 7) suggests an underestimation of capabilities that could be construed as evidence of a protective mechanism employed to preserve homeostasis. In an unsupervised exercise environment, the sensations that influence the elevated levels of RPE and PTD in the early stages of the IIF60 task may prompt an overly cautious approach to the exercise bout and, therefore, result a sub-optimal performance. However, this element of caution is preferable to an overestimation of performance that may lead to an unexpected onset of task failure, as reflected in the PTD responses during the IIF80 task (Chapter 6). Although the higher intensity and shorter duration IIF80 did provoke inaccurate PTD responses, implying an overestimation of performance capability, the reaction of disappointment apparent in some participants may suggest that they were unaware of the higher IIF target force. It is plausible that participants may have under-reported of self-perception in a bid to appear more capable in the presence of the experimenters (Lewthwaite 1990). Further research is therefore required before concluding if these PTD responses provide an example of inaccurate judgement, or are instead caused by this situational factor.

When considering the current findings in the context of previous literature, patterns of perceptual response during exercise may be specific to both the mode and intensity of the task. RPE scales and prediction of TD may provide greater benefit in optimising performance during closed-loop endurance events such as running or cycling, where participants have considerable experience in performing the tasks and the associated perceptual cues arising from the activity. More research is required before establishing the efficacy of self-perception with regard to providing an accurate indication of exercise duration in isolated muscle activity. Based on these current findings, these perceptual scales would appear to have limited utility in a clinical population, where the disruption resulting from injury, surgery and de-conditioning could likely increase inter-individual variation in response.

8.4. RECOMMENDATIONS FOR FUTURE RESEARCH

Due to the inherent problems associated with exploring the efficacy of RPE during novel exercise tasks (as highlighted in section 8.3.1), it may be more pertinent to refine the research question and adopt an alternative approach. Given that sub-optimal knee and hip biomechanics during jump landings have been implicated in a fatigue-related increase in ACL injury risk (McLean and Samorezov 2009), an alternative direction for future research could focus on performers' ability to accurately perceive an impairment of technique as a consequence of fatigue. Significant impairments to knee and hip biomechanics during single-leg landings have previously been observed at the conclusion of a repeated squatting task (Borotikar et al., 2008). Interestingly, biomechanics were similarly impaired at 50% of the duration of the squatting task, suggesting that injury risk may increase considerably earlier than task failure. Although previous research has explored RPE as a predictor of duration during repeated jumping tasks, attention was focused on achieving a specified jump height with no reference made to deterioration of landing technique. In this regard it may be worthwhile to investigate whether performers can perceive deterioration in technique as they are exposed to increasing levels of fatigue. The ability to identify a critical point at which technique becomes significantly impaired may assist in the self-regulation of exercise in terms of minimising injury risk.

8.5. CONCLUDING REMARKS

Much of the previous literature related to the issue of pacing and self-regulation of exercise has focused on continuous running and cycling activities, utilising trained and competitive endurance athletes. However, the concept of optimising performance and maintaining homeostasis is equally important in rehabilitative scenarios, where patients aim to accelerate a return to competitive sport and minimise risk of re-injury. A considerable amount of rehabilitation will be undertaken without the benefit of specialist supervision, thus relying on the judgement of the patient to self-regulate their recovery. Whereas endurance athletes will be well trained and highly familiar with the sensory cues arising from their specific mode of exercise, ACL-reconstructed patients will be relatively unfamiliar with various components of rehabilitation, especially following extended periods of restricted activity. Moreover, the consequences of surgery provide the additional challenge of a severe perturbation to the knee joint, resulting in changes to afferent feedback mechanisms.

The research reported in this thesis has questioned the utility of self-perceived capabilities, both in regard to estimating knee function and also providing an accurate indication of task duration during novel and intermittent isolated muscle exercise that is commonplace during recovery from reconstructive surgery. Given the current findings, further investigation is required before self-perception measures can be recommended to assist with monitoring and self-regulating exercise progressions during rehabilitation.

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APPENDICES

Appendix A

International Knee Documentation Committee Subjective Knee Evaluation Form

2000 IKDC SUBJECTIVE KNEE EVALUATION FORM

Your Full Name____

Today's Date: ______/_______/______ (Day / Month / Year)   Date of Injury: ______/________/_____ (Day / Month / Year)

SYMPTOMS*:

*Grade symptoms at the highest activity level at which you think you could function without significant symptoms, even if you are not actually performing activities at this level.

1. What is the highest level of activity that you can perform without significant knee pain?

   4❑Very strenuous activities like jumping or pivoting as in basketball or soccer
   3❑Strenuous activities like heavy physical work, skiing or tennis
   2❑Moderate activities like moderate physical work, running or jogging
   1❑Light activities like walking, housework or yard work
   0❑Unable to perform any of the above activities due to knee pain

2. During the past 4 weeks, or since your injury, how often have you had pain?

	10	9	8	7	6	5	4	3	2	1	0	
Never	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	Constant

3. If you have pain, how severe is it?

	10	9	8	7	6	5	4	3	2	1	0	
No pain	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	Worst pain imaginable

4. During the past 4 weeks, or since your injury, how stiff or swollen was your knee?

   4❑Not at all
   3❑Mildly
   2❑Moderately
   1❑Very
   0❑Extremely

5. What is the highest level of activity you can perform without significant swelling in your knee?

   4❑Very strenuous activities like jumping or pivoting as in basketball or soccer
   3❑Strenuous activities like heavy physical work, skiing or tennis
   2❑Moderate activities like moderate physical work, running or jogging
   1❑Light activities like walking, housework, or yard work
   0❑Unable to perform any of the above activities due to knee swelling

6. During the past 4 weeks, or since your injury, did your knee lock or catch?

   0❑Yes   1❑No

7. What is the highest level of activity you can perform without significant giving way in your knee?

   4❑Very strenuous activities like jumping or pivoting as in basketball or soccer
   3❑Strenuous activities like heavy physical work, skiing or tennis
   2❑Moderate activities like moderate physical work, running or jogging
   1❑Light activities like walking, housework or yard work
   0❑Unable to perform any of the above activities due to giving way of the knee

SPORTS ACTIVITIES:

8. What is the highest level of activity you can participate in on a regular basis?

   4❑Very strenuous activities like jumping or pivoting as in basketball or soccer
   3❑Strenuous activities like heavy physical work, skiing or tennis
   2❑Moderate activities like moderate physical work, running or jogging
   1❑Light activities like walking, housework or yard work
   0❑Unable to perform any of the above activities due to knee

9. How does your knee affect your ability to:

		Not difficult at all	Minimally difficult	Moderately Difficult	Extremely difficult	Unable to do
a.	Go up stairs	4❑	3❑	2❑	1❑	0❑
b.	Go down stairs	4❑	3❑	2❑	1❑	0❑
c.	Kneel on the front of your knee	4❑	3❑	2❑	1❑	0❑
d.	Squat	4❑	3❑	2❑	1❑	0❑
e.	Sit with your knee bent	4❑	3❑	2❑	1❑	0❑
f.	Rise from a chair	4❑	3❑	2❑	1❑	0❑
g.	Run straight ahead	4❑	3❑	2❑	1❑	0❑
h.	Jump and land on your involved leg	4❑	3❑	2❑	1❑	0❑
i.	Stop and start quickly	4❑	3❑	2❑	1❑	0❑

FUNCTION:

10. How would you rate the function of your knee on a scale of 0 to 10 with 10 being normal, excellent function and 0 being the inability to perform any of your usual daily activities which may include sports?

FUNCTION PRIOR TO YOUR KNEE INJURY:

Couldn't perform daily activities	0	1	2	3	4	5	6	7	8	9	10	No limitation in daily activities
	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	

CURRENT FUNCTION OF YOUR KNEE:

Cannot perform daily activities	0	1	2	3	4	5	6	7	8	9	10	No limitation in daily activities
	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	

Appendix B

Indices of self-perceived function and musculoskeletal performance during ACL rehabilitation period (group means ± SD)

Index		Assessment Session				
		Pre-surgery	+6 weeks	+12 weeks	+24 weeks	+48 weeks
Self-Perceived Measures						
PP	(%)	54.7 ± 14.1	55.3 ± 18.3	70.1 ± 18.4	80.5 ± 15.2	92.3 ± 7.8
IKDC	(%)	51.4 ± 8.9	40.9 ± 9.4	67.8 ± 15.2	81.5 ± 14.8	88.6 ± 9.0
Musculoskeletal Performance						
ATFD	(mm)					
INJ		13.3 ± 2.7	5.8 ± 1.6	6.0 ± 1.1	3.3 ± 1.0	2.7 ± 0.5
NON		2.7 ± 0.5	2.6 ± 0.5	4.3 ± 0.5	2.2 ± 0.5	2.6 ± 0.6
PF	(N)					
INJ_{KE}		408.4 ± 122.2	264.2 ± 71.3	332.4 ± 90.8	357.0 ± 97.3	395.6 ± 104.8
NON_{KE}		455.5 ± 124.9	466.8 ± 125.6	495.2 ± 131.5	454.5 ± 124.2	472.9 ± 128.5
INJ_{KF}		238.0 ± 94.1	174.0 ± 56.0	225.7 ± 73.4	254.7 ± 81.6	266.0 ± 85.1
NON_{KF}		251.9 ± 77.6	261.4 ± 82.2	269.0 ± 83.8	273.8 ± 86.1	273.2 ± 83.7
RFD	($N^{.s-1}$)					
INJ_{KE}		2900 ± 1428	2869 ± 1583	3552 ± 1830	4099 ± 2136	3354 ± 1674
NON_{KE}		3820 ± 1920	3715 ± 1929	3537 ± 1759	3933 ± 2042	4220 ± 2129
INJ_{KF}		2930 ± 1446	2868 ± 1604	3530 ± 1813	4155 ± 2158	3324 ± 1645
NON_{KF}		3845 ± 1930	3751 ± 1950	3543 ± 1756	3891 ± 2034	4241 ± 2140
HOP	(cm)					
INJ		110.5 ± 40.5	93.7 ± 24.7	108.6 ± 30.0	122.2 ± 32.1	119.2 ± 30.7
NON		128.7 ± 35.1	146.8 ± 40.3	137.1 ± 36.0	133.9 ± 36.3	144.0 ± 39.2

Appendix C

Participant Information for studies 2 and 3 (Chapters 4 and 5)

Participant Information Sheet

"RELATIONSHIP BETWEEN SELF-PERCEPTION AND TIME-TO-END-POINT IN AN INTERMITTENT ISOMETRIC EXERCISE TASK"

- ## Introduction:

Thank you for agreeing to participate in this study.

In sporting activity, pacing involves the performance of a given event at optimal intensity and with optimal energy consumption. A marathon runner, for example, would not want to run at a pace so slow that the event would take all day, but also not run so fast that they could not maintain the pace. Whilst there are a variety of different types of pacing depending on the activity, it is suggested that the performer's perception of effort plays an integral part in the pacing process. It has been proposed that effort perception results from the interpretation of sensory feedback from the body, matched against an anticipated outcome based on the performer's prior experience.

This study will (a) explore the relationship between the performer's self-perception of effort and the time-to-end-point in a bout of exercise using the thigh muscles (quadriceps), and (b) how this relationship changes with experience over three separate testing sessions.

- ## Study Requirements:

You will be required to attend an initial familiarisation session, followed by three subsequent testing sessions each separated by 48-72 hours. Each session is likely to last around 45 minutes.

- ## Location:

The procedure will take place in the biomechanics laboratory in the CELS building at Nottingham Trent University.

- ## Restrictions During Testing:

Please refrain from exercising in the 24-hours prior to the test.

- ## Testing Protocol:

The testing will require you to perform a static fatigue task for your quadriceps muscles. This task will consist of sets of ten sub-maximal muscular efforts (knee extensions) performed at a work: rest ratio of 1s:1s. After the final effort in each set, you will be asked to record some measures of how hard you think you are working. The fatigue task concludes at the end of any set in which you have been unable to maintain the target force for 3 consecutive efforts, or for the majority of the efforts within the set.

Before and after the fatigue task, a profile of measurements of your muscle performance will be calculated subsequent to your own volitional brief maximal muscle activation and from single-pulse magnetically-evoked muscle stimulation.

The quadriceps muscles will also be monitored for levels of activity during the testing using surface electrodes. These electrodes will be placed over the involved muscles, and the skin around these areas will require shaving and cleaning to provide optimal conductivity.

• Potential Benefits to You

This testing will help to improve your interpretation of the sensations of effort and fatigue in relation to how long you believe you can keep going during a bout of exercise. This information may help you to pace yourself more effectively during sporting activity.

• Potential Risks to You

You may experience some discomfort during the fatigue trial. However, you are free to withdraw from the study at any time. Data collected may be presented in various forms (journal articles, papers etc.), but personal information will be treated in confidence. No names will be associated with data in presentations.

• Contacts

Joe Shepherd (investigator)
Tel: 07886 485727
Email: joseph.shepherd@ntu.ac.uk

Statement of consent to participate in the investigation entitled:

"RELATIONSHIP BETWEEN SELF-PERCEPTION AND TIME-TO-END-POINT IN AN INTERMITTENT ISOMETRIC EXERCISE TASK"

Primary Researcher: Joseph Shepherd
First Supervisor: Claire Minshull
Second Supervisor: Kirsty Hunter

I (subject name) ……………………………………… have read the information provided and agree to partake, as a subject in the proposed research entitled: ………...

I am fully aware of the procedures to be carried out and have been informed of any risks they may present. I agree to obey the universities regulations and the investigators instructions regarding safety matters.

I am aware that I may withdraw my consent to participate in the research at any time without any obligation to explain why or any prejudice towards them.

I also understand that any personal information regarding myself will not be passed to and other parties.

I understand that I will not be informed of any genotype.

I have completed the health screening questionnaire and know of no other reasons, medical or otherwise, that will prevent me from partaking in this research.

Signed (Subject)…………………………………………………………………. Date ………………………..

Signed (Independent Witness)………………………………………….. Date………………………….

Signed (Primary Researcher) ……………………………………………. Date………………………….

HEALTH SCREEN

Name or Number ....………………

Please complete this brief questionnaire to confirm fitness to participate:

1. **At present,** do you have any health problem for which you are:

(a) on medication, prescribed or otherwise Yes ☐ No ☐

(b) attending your general practitioner Yes ☐ No ☐

(c) on a hospital waiting list Yes ☐ No ☐

2. **In the past two years,** have you had any illness which require you to:

(a) consult your GP Yes ☐ No ☐

(b) attend a hospital outpatient department Yes ☐ No ☐

(c) be admitted to hospital Yes ☐ No ☐

3. **Have you ever** had any of the following?

(a) Convulsions/epilepsy Yes ☐ No ☐

(b) Asthma Yes ☐ No ☐

(c) Eczema Yes ☐ No ☐

(d) Diabetes Yes ☐ No ☐

(e) A blood disorder Yes ☐ No ☐

(f) Head injury Yes ☐ No ☐

(g) Digestive problems Yes ☐ No ☐

(h) Heart problems Yes ☐ No ☐

(i) Problems with bones or joints Yes ☐ No ☐

(j) Disturbance of balance / coordination Yes ☐ No ☐

(k) Numbness in hands or feet Yes ☐ No ☐

(l) Disturbance of vision Yes ☐ No ☐

(m) Ear / hearing problems Yes ☐ No ☐

(n) Thyroid problems Yes ☐ No ☐

(o) Kidney or liver problems Yes ☐ No ☐

(p) Allergy to nuts, alcohol etc Yes ☐ No ☐

4. **Has any,** otherwise healthy, member of your family under the age of 35 died suddenly during or soon after exercise? Yes ☐ No ☐

5. Are there any reasons why blood sampling may be difficult? Yes ☐ No ☐

6. Have you had a blood sample taken previously? Yes ☐ No ☐

7. Have you had a cold or flu or any flu like symptoms in the last month? Yes ☐ No ☐

Appendix D

Participant Information for studies 4 and 5 (Chapters 6 and 7)

Participant Information Sheet

"THE EFFECT OF EXERCISE-INDUCED MUSCLE DAMAGE ON SELF-PERCEPTION DURING AN INTERMITTENT FATIGUE TASK."

- Introduction:

Thank you for agreeing to participate in this study.

In sporting activity, pacing involves the performance of a given event at optimal intensity and with optimal energy consumption. A marathon runner, for example, would not want to run at a pace so slow that the event would take all day, but also not run so fast that they could not maintain the pace. Whilst there are a variety of different types of pacing depending on the activity, it is suggested that the performer's perception of effort plays an integral part in the pacing process. It has been proposed that effort perception results from the interpretation of sensory feedback from the body, matched against an anticipated outcome based on the performer's prior experience.

This study will (a) explore the relationship between the performer's self-perception of effort and the time-to-end-point in a bout of exercise using the thigh muscles (quadriceps), and (b) how exercise-induced muscle damage affects this relationship.

- Study Requirements:

You will be required to attend an initial familiarisation session, followed by two subsequent testing days each separated by 24 hours. Each testing day is likely to last around 3 hours.

- Location:

The procedure will take place in the biomechanics laboratory in the CELS building at Nottingham Trent University.

- Restrictions During Testing:

Please refrain from strenuous exercise in the 24-hours prior to each testing day.

- Testing Protocol:

The testing will require you to perform a static fatigue task for your quadriceps muscles. This task will consist of sets of ten sub-maximal muscular efforts (knee extensions) performed at a work: rest ratio of 1s:1s. After the final effort in each set, you will be asked to record some measures of how hard you think you are working. The fatigue task concludes at the end of any set in which you have been unable to maintain the target force for 3 consecutive efforts, or for the majority of the efforts within the set.

Before and after the fatigue task, a profile of measurements of your muscle performance will be calculated subsequent to your own volitional brief maximal muscle activation and from single-pulse magnetically-evoked muscle stimulation.

The quadriceps muscles will also be monitored for levels of activity during the testing using surface electrodes. These electrodes will be placed over the involved muscles, and the skin around these areas will require shaving and cleaning to provide optimal conductivity.

You will also be randomly assigned to one of two groups: 1) an eccentric exercise-induced muscle damage (EIMD) condition; 2) a control group (rest of equivalent duration to EIMD intervention). The EIMD intervention or equivalent period of control will be performed one hour following the cessation of the fatigue task on the first test session only. The EIMD condition will comprise 10 x 10 sets maximal eccentric knee extensions on an isokinetic dynamometer on the dominant limb.

- Potential Benefits to You

This testing will help to improve your interpretation of the sensations of effort and fatigue in relation to how long you believe you can keep going during a bout of exercise. This information may help you to pace yourself more effectively during sporting activity.

- Potential Risks to You

You may experience some discomfort during the fatigue trial, and may also experience feelings of discomfort and soreness in the involved musculature following the EIMD exercise intervention. However, you are free to withdraw from the study at any time. Data collected may be presented in various forms (journal articles, papers etc.), but personal information will be treated in confidence. No names will be associated with data in presentations.

- Contacts

Joe Shepherd (investigator)
Tel: 07886 485727
Email: joseph.shepherd@ntu.ac.uk

Statement of consent to participate in the investigation entitled:

"THE EFFECT OF EXERCISE-INDUCED MUSCLE DAMAGE ON SELF-PERCEPTION DURING AN INTERMITTENT FATIGUE TASK."

Primary Researcher: Joseph Shepherd
Director of Studies: Claire Minshull

I (subject name) ……………………………………… have read the information provided and agree to partake, as a subject in the proposed research entitled:
"The effect of exercise-induced muscle damage on self-perception during an intermittent fatigue task."

I am fully aware of the procedures to be carried out and have been informed of any risks they may present. I agree to obey the universities regulations and the investigators instructions regarding safety matters.

I am aware that I may withdraw my consent to participate in the research at any time without any obligation to explain why or any prejudice towards them.

I also understand that any personal information regarding myself will not be passed to and other parties.

I have completed the health screening questionnaire and know of no other reasons, medical or otherwise, that will prevent me from partaking in this research.

Signed (Subject)………………………………………………………………. Date ………………………..

Signed (Independent Witness)………………………………………….. Date………………………….

Signed (Primary Researcher) ……………………………………………. Date………………………….

HEALTH SCREEN

Name or Number ....………………

Please complete this brief questionnaire to confirm fitness to participate:

1. **At present,** do you have any health problem for which you are:

(a) on medication, prescribed or otherwise Yes ☐ No ☐

(b) attending your general practitioner Yes ☐ No ☐

(c) on a hospital waiting list Yes ☐ No ☐

2. **In the past two years,** have you had any illness which require you to:

(a) consult your GP Yes ☐ No ☐

(b) attend a hospital outpatient department Yes ☐ No ☐

(c) be admitted to hospital Yes ☐ No ☐

3. **Have you ever** had any of the following?

(a) Convulsions/epilepsy Yes ☐ No ☐

(b) Asthma Yes ☐ No ☐

(c) Eczema Yes ☐ No ☐

(d) Diabetes Yes ☐ No ☐

(e) A blood disorder Yes ☐ No ☐

(f) Head injury Yes ☐ No ☐

(g) Digestive problems Yes ☐ No ☐

(h) Heart problems Yes ☐ No ☐

(i) Problems with bones or joints Yes ☐ No ☐

(j) Disturbance of balance / coordination Yes ☐ No ☐

(k) Numbness in hands or feet Yes ☐ No ☐

(l) Disturbance of vision Yes ☐ No ☐

(m) Ear / hearing problems Yes ☐ No ☐

(n) Thyroid problems Yes ☐ No ☐

(o) Kidney or liver problems Yes ☐ No ☐

(p) Allergy to nuts, alcohol etc Yes ☐ No ☐

4. **Has any,** otherwise healthy, member of your family under the age of 35 died suddenly during or soon after exercise? Yes ☐ No ☐

5. Are there any reasons why blood sampling may be difficult? Yes ☐ No ☐

6. Have you had a blood sample taken previously? Yes ☐ No ☐

7. Have you had a cold or flu or any flu like symptoms in the last month? Yes ☐ No ☐