Torque it up: reliability and variability of isokinetic peak torque and angle of peak torque

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Abstract

Introduction: Muscular performance is commonly tested using isokinetic dynamometry, with traditional protocols consisting of grouped repetitions and small rest periods between sets. Despite its popularity, current isokinetic testing assumes that the within-subject variation of angle of peak torque is low, and that most of the biological variability of peak torque and angle of peak torque is accounted for. Other assumptions of isokinetic testing include that the: (i) force output and behaviour of skeletal muscle is constant from one repetition to another, (ii) highest peak torque is achieved within five grouped repetitions, and (iii) torque-angle relationship is a static phenomenon and also represents sarcomere length. Previous and current isokinetic strength testing either ignores many factors of force production or assumes that they do not influence the biological variability and ultimately the within-subject variation of peak torque and angle of peak torque. Controlling for some factors of force production may yield a higher peak torque and a smaller Standard Error of Measurement (SEM) and Minimal Detectable Change (MDC) of peak torque and its angle, thus improving the reliability of such strength testing. The primary aim of this study was to determine and describe the within-session reliability of peak torque and angle of peak torque. This was tested using isokinetic concentric knee extensions at 60°/s across three different repetition protocols.

Methods: Twenty four physically active male participants (23 ± 3 y, 77.9 ± 7.9 kg) performed 50 maximal concentric knee extensions of their dominant limb at 60°/s on a Biodex System II isokinetic dynamometer, in three different sessions 2 - 6 days apart. Prior to these sessions no warm up was performed. The three sessions consisted of: (i) ten sets of five grouped repetitions with a 120-s rest between sets (Gr-R), (ii) 50 interspersed repetitions with a 30-s rest between repetitions (IR-30), and (iii) 50 interspersed repetitions with a 60-s rest between repetitions (IR-60).

Results: SEM (MDC) of peak torque over the first two repetitions were 12 (33) N.m, 11 (30) N.m and 13 (35) N.m for Gr-R, IR-30 and IR-60, respectively. SEM (MDC) of angle of peak torque over the first five repetitions was 4° (10°) for Gr-R, whereas over the first two repetitions it was 4° (11°) and 4° (10°) for IR-30 and IR-60 respectively. Mean peak torque across 50 repetitions was higher ($p < 0.01$) using IR-60 (243 N.m) and IR-30 (242 N.m) protocols than the Gr-R protocol (231 N.m). The obtained maximal peak torque of all 50 repetitions was higher compared to that of the first five repetitions, by 11%, 10%, and 7% for Gr-R, IR-30 and IR-60, respectively. 38% of participants achieved their highest peak torque between repetitions 11-20 and 1-10 for Gr-R and IR-60 respectively, and 33% of participants achieved their highest peak torque between repetitions 41-50 for IR-30.

Conclusion: Only two grouped or interspersed repetitions of concentric knee extension tested isokinetically at 60°/s are required to obtain a reliable peak torque within a session. Whereas for angle of peak torque, five grouped and two interspersed repetitions of isokinetic knee extension are required to obtain a reliable measure. If the purpose of testing is to achieve the highest peak torque possible, then repetitions should be separated by a rest period (30-s or 60-s in the current study) rather than grouped in sets of consecutive repetitions. Individuals clearly differ as to when they achieve their highest peak torque, so more than the traditional five repetitions are necessary for most individuals. The transient increase of peak torque with repetitions, particularly for interspersed repetitions with a 30-s rest, may possibly be due to an augmentation of muscle properties or other muscular factors over time.

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List of Abbreviations

ATP	Adenosine triphosphate
CV	Coefficient of variation
CNS	Central nervous system
Gr-R	Grouped repetition protocol
GTO	Golgi tendon organ
ICC	Intraclass correlation coefficient
IR-30	Interspersed repetition protocol with a 30-s rest
IR-60	Interspersed repetition protocol with a 60-s rest
LOA	Limits of agreement
MDC	Minimal detectable change
N.m	Newton meters
PCr	Phosphocreatine
PAP	Post-activation potentiation
SEM	Standard error of measurement
Tm	Muscle temperature
VAS	Visual analogue scale

Chapter 1 - Introduction

1.1 Introduction to the problem

Muscular strength is the ability of a muscle or muscle groups to generate force and is essential to human movement (Baechle & Earle, 2000). Threshold levels of force are required to effectively perform and complete daily movements such as walking, climbing stairs, moving from sitting to standing, and lifting or carrying objects. Therefore, muscular strength is directly linked to an individual's functional capacity and musculoskeletal fitness.

Muscular strength is also important for athletic performance. High levels of force are required for the completion and performance of certain athletic movements such as tackling in rugby, kicking a football or throwing a javelin. The ability to produce a high level of muscular force within a movement results in a high level of muscular power (Enoka, 2002), which in turn improves one's ability to rapidly apply force and move a body segment or an external object.

Assessing muscular ability is important because the magnitude of force generated and applied by an individual indicates their muscular function and functional capacity. Strength testing also allows one to identify weaker muscle groups which may have an impaired function or predispose individuals to injury (Brown, 2000). Therefore, knowledge of the strength or weakness of a particular muscle group during a given movement has important implications for an individual's rehabilitation, function and injury prevention.

Isokinetic dynamometry is used to assess muscular performance in a variety of settings such as scientific research, clinical rehabilitation, and exercise training or testing (Nitschke, 1992; Chan, Maffulli, Korkia & Li, 1996). It is used for many reasons which include: (i) the assessment of muscular strength or injuries, which may inform training and rehabilitative programs (Keating & Matyas, 1996; Nitschke, 1992) (ii) attaining standardised pre and post measures for a training intervention; (iii) providing a physiological profile of an athlete which can be compared to normative data (Goslin & Charteris, 1979); (iv) correlating torque

measures to other factors or tests such as electromyography, sprinting or jumping (Keating & Matyas, 1996); and (v) as a training aid for athletic performance or rehabilitation (Chan et al., 1996).

Isokinetic dynamometry involves the measurement of a muscular action against a motor controlled exercise machine, with the movement performed at a constant angular velocity (Baltzopoulos & Brodie, 1989). During isokinetic testing an individual's joint is aligned with the axis of rotation of the dynamometer and force is exerted against the lever arm. Torque is the rotational effect of a force about an axis and is measured as force is applied to the lever arm (Baltzopoulos & Brodie, 1989). Each movement of the lever arm is normally performed at maximal effort resulting in a torque-angle curve or relationship of a particular joint action.

The torque-angle relationship describes the variation of torque with joint angle, whereby a certain level of torque is produced at certain joint angles, as shown in **Error! Reference source not found.**. It is a fundamental property of human movement as it occurs during everyday tasks such as lifting an object and sporting movements such as sprinting. The measurement of torque is important as it reflects muscular force and function. Two common measures used in isokinetic dynamometry are peak torque and angle of peak torque. Peak torque is the single highest level of torque produced during a given movement (Kannus, 1994). Angle of peak torque is the joint angle of a given movement at which peak torque occurs. It has been hypothesised that angle of peak torque may indicate potential risk of muscular injury (Brockett, Morgan and Proske, 2001). Angle of peak torque has been claimed to be reliably measured by Brockett, Morgan and Proske (1999) but there is no thorough scientific evidence that substantiates this claim. A large majority of angle of peak torque literature base the reliability of their measures on this claim, and they have not critically examined the evidence of previous angle of peak torque studies. So with no rigorous scientific evidence to support such a claim the measures of angle of peak torque within these articles is also questionable.

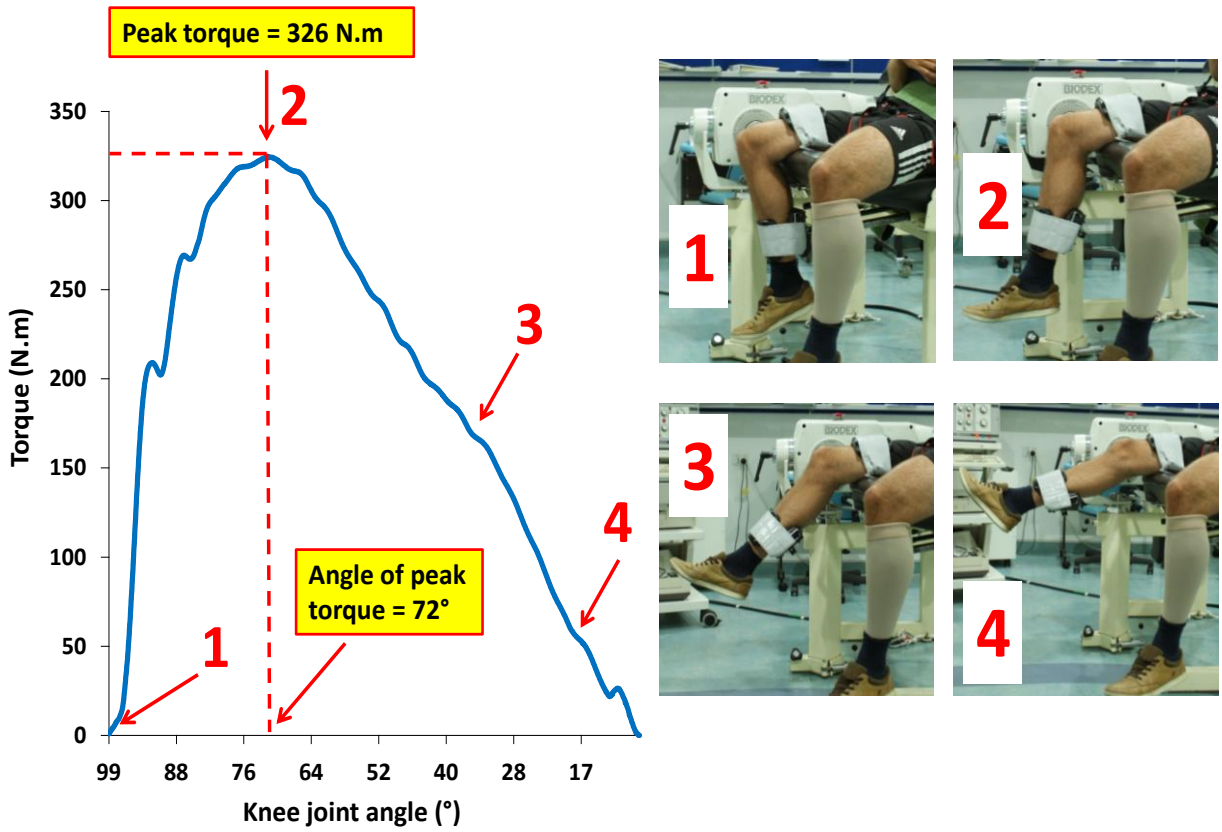


Figure 1. Example of the torque-angle relationship during isokinetic knee extension

Some of the assumptions of isokinetic testing include that: (i) angle of peak torque is reliably measured (Brockett et al., 1999; Brockett et al., 2001; Bowers, Morgan and Proske, 2004; Brughelli, Cronin and Nosaka, 2010a; Brughelli et al., 2010b), (ii) the torque-angle relationship is a static phenomenon and also represents sarcomere length (Brockett et al. 1999; Brockett et al. 2001), (iii) the force output and behaviour of skeletal muscle is constant from one repetition to another (Brown, 2000; Chan et al., 1996; Brockett et al. 1999; Brockett et al. 2001), and (iv) the highest peak torque is achieved within 2 – 6 grouped repetitions and during reciprocal movements (Baltzopoulos & Brodie, 1989; Brown & Weir, 2001; Johnson & Siegel, 1978; Sawhill, Bates, Osternig & Hamill, 1982).

The majority of isokinetic research has focused on movements of knee extension and flexion (Chan, et al., 1996). One common aspect between isokinetic testing protocols for knee extension and flexion is that only one set of repetitions for each velocity is tested, with slow

velocities completed prior to fast velocities. However, the number of repetitions, velocities, rest periods, type of contractions and movements used between protocols are inconsistent. The inconsistency between protocols highlights the fact that there is not a universal isokinetic testing protocol.

Testing protocols normally consist of:

(i) Two to six maximal grouped or interspersed repetitions (Ayala, De Ste Croix, Sainz de Baranda, & Santonja, 2012; Bernard et al., 2012; Almosnino, Stevenson, Bardana, Diaconescu & Dvir, 2012). Interspersed repetitions consist of a rest period between repetitions, and in the reviewed studies this was either 15-s or 30-s (Sole, Hamren, Milosavljevic, Nicholson & Sullivan, 2007; Bemben & Johnson, 1993). Grouped repetitions consist of consecutive repetitions with a rest period between sets.

(ii) One to five different angular velocities tested, ranging from 60°/s to 450°/s (Brown, Whitehurst, Bryant & Buchalter, 1993; Impellizzeri, Bizzini, Rampinini, Cereda & Maffiuletti, 2008; Brown, Whitehurst & Bryant, 1992)

(iii) Rest periods ranging from 1 to 5 min between tested angular velocities (Bernard et al., 2012; Almosnino et al., 2012).

(iv) Reciprocal repetitions in which each knee extension is immediately followed by a knee flexion repetition, or non reciprocal movements in which knee extension or flexion are performed separately.

(v) Concentric contractions of knee extension and flexion with no eccentric contraction.

(vi) Concentric contractions directly followed eccentric contractions of knee extension or flexion

These isokinetic testing protocols are based upon several assumptions. Firstly it assumes that peak torque and angle of peak torque are consistent phenomena, and that angle of peak

torque has a low within-subject variation. Measurement error causes the observed value of a measure to differ from the true value (Hopkins, 2000). Within-subject variation is the fluctuation of a measure from one trial to another, due to errors of measurement (Hopkins, 2000). Two common forms of within-subject variation include Standard Error Measurement (SEM) and Coefficient of Variation (CV). SEM is sometimes referred to as typical error particularly by Hopkins (2000), but SEM is the preferred term for this thesis. Within-subject variation is a measure of reliability and reflects the reproducibility or repeatability of a measure (Hopkins, 2000). For example, angle of peak torque would be regarded as having a low within-subject variation if the values from repeated measures showed minimal fluctuations. A large variation between measures makes it difficult to know whether these measured changes are true or just part of the measurement error. Large variations degrade the precision of the measure and the ability to track changes between single or repeated measurements. Smaller variation between measures means one can be more confident of measuring true changes. Therefore knowledge of the within-subject variation (e.g. SEM or CV) of a measure prior to testing is integral in order to know how much measurement error is associated with it and to quantify how much of a change may have occurred in a given measure.

One main source of within-subject variation is biological variability (Hopkins, 2000). Biological variability comes from changes in the physical or mental state of the participant. The majority of the isokinetic reliability studies have shown peak torque during concentric knee extension to have very good to high within and between-session reliability across a velocity spectrum (Almosnino et al., 2012; Impellizzeri et al., 2008; Sole et al., 2007; Brown et al., 1992). In contrast, angle of peak torque has predominantly been shown to have poor within and between-session reliability during concentric knee extension (Ayala et al., 2012; Phillips, Sing & Mastaglia, 2000; Bemben & Johnson, 1993; Brown et al., 1993; Wilhite, Cohen & Wilhite, 1992).

The current protocols of isokinetic testing assume that most of the biological variability of peak torque and angle of peak torque are controlled for. However, force output is not only determined by contractile factors, but also intrinsic properties of the musculotendinous unit, metabolic and neural factors, and recent movement history. Present isokinetic test protocols either ignore these factors or assume that they do not influence the biological variability and ultimately the within-subject variation of peak torque and angle of peak torque. If isokinetic testing protocols performed more repetitions and had more of a rest between repetitions they may account for some of the factors suggested to cause the variability of torque output. Thus, the within-subject variation and reliability of angle of peak torque might be lower, and a higher magnitude of peak torque could be obtained if such changes were made.

1.2 Statement of the problem

No previous literature has investigated the consistency and behaviour of peak torque and angle of peak torque over time with multiple grouped and interspersed repetitions. The current literature does not justify why certain velocities, number of repetitions, rest periods and contractions types are used in testing. Nor does it account for factors which could cause some of the observed biological variability of peak torque and angle of peak torque. What is unknown is how the movement history of grouped and interspersed repetitions influences peak torque and angle of peak torque, and thus the torque-angle relationship. The aim of this study was to describe the within-session reliability of peak torque and angle of peak torque across grouped and interspersed repetition protocols.

1.3 Objectives and hypotheses

The objectives of this research were:

To describe the Standard Error of Measurement and Minimal Detectable Change of peak torque and angle of peak torque within a session during concentric knee extension tested isokinetically at 60°/s across (i) a grouped repetition protocol, and (ii) interspersed repetition protocols.

A secondary aspect of this thesis was also to explore and describe peak torque and angle of peak torque over 50 repetitions of concentric knee extension tested isokinetically at 60°/s across interspersed and grouped repetition protocols.

This thesis is comprised of five different alternative hypotheses:

H_1: Peak torque production will be reliable for grouped repetitions.

H_2: The angle at which peak torque is produced will not be reliable for grouped repetitions.

H_3: Peak torque production will be reliable for interspersed repetitions.

H_4: The angle at which peak torque is produced will not be reliable for grouped repetitions.

H_5: Peak torque production will be higher during interspersed repetitions.

1.4 Significance

Peak torque and angle of peak torque measurements are the basis for making clinical decisions and interpreting the impact of research interventions. Establishing the within-subject variation of peak torque and angle of peak torque will allow for true changes in these measures to be assessed and accurate tracking of changes in such measures. Understanding the time frame involved in obtaining a reliable measure of peak torque and angle of peak torque is important for testing isokinetic knee extension. The isokinetic strength testing and reliability literature is substantive and has focused on grouped repetitions with varied rest periods,

velocities and number of repetitions. This literature does not appear to consider that force production is a dynamic quality resulting from many interacting factors.

The current study is the first to provide a description of human torque production over multiple interspersed and grouped repetitions of isokinetic knee extension. Peak torque and angle of peak torque are measured in a variety of research and exercise settings, however the actual behaviour of these measures over multiple interspersed repetitions is still unknown. This study will provide an understanding of the effects of the movement history of grouped and interspersed repetitions on torque production. Understanding the behaviour of peak torque and angle of peak torque will create a platform to study the exact mechanisms contributing to torque production, and will help provide a guideline for a universal isokinetic testing protocol.

Chapter 2 - Review of Literature

2.1 Introduction to the chapter

This review is divided into two sections. Although mechanisms of force production were not measured in the current study, the purpose of the first section of this review is to describe factors that influence musculoskeletal force production. In particular it will focus on some factors that change during muscular contractions. The second section will review the possible significance of angle of peak torque, measures of reliability used in isokinetic dynamometry and reliability studies of isokinetic knee extension. Aspects discussed in the first section include: (i) the model of the musculotendinous unit, (ii) recent movement history, (iii) central nervous system and motor control, (iv) motor units, (v) intrinsic properties of muscle, (vi) tendon structure and function, (vii) compliance and stiffness, (viii) proprioceptors and reflex arcs, (ix) phosphocreatine depletion and resynthesis, (x) muscle temperature, (xi) Post-Activation Potentiation (PAP), and (xii) fascicle length and pennation angle,

2.2 Factors influencing force production

Muscular force is dependent on many different dynamic factors and processes including higher control centres of the Central Nervous System (CNS), reflex arcs, recent movement history and intrinsic properties of the musculotendinous unit. During repeated muscular contractions some factors may change, optimise and stabilise at different points in time, which may result in different magnitudes of force with each repetition. Factors that influence muscular force production are outlined in figure 2. The different behaviour of these factors over time may lead to variations in force production. Factors with an asterisk (*) in figure 2 denote those that change during muscular contractions.

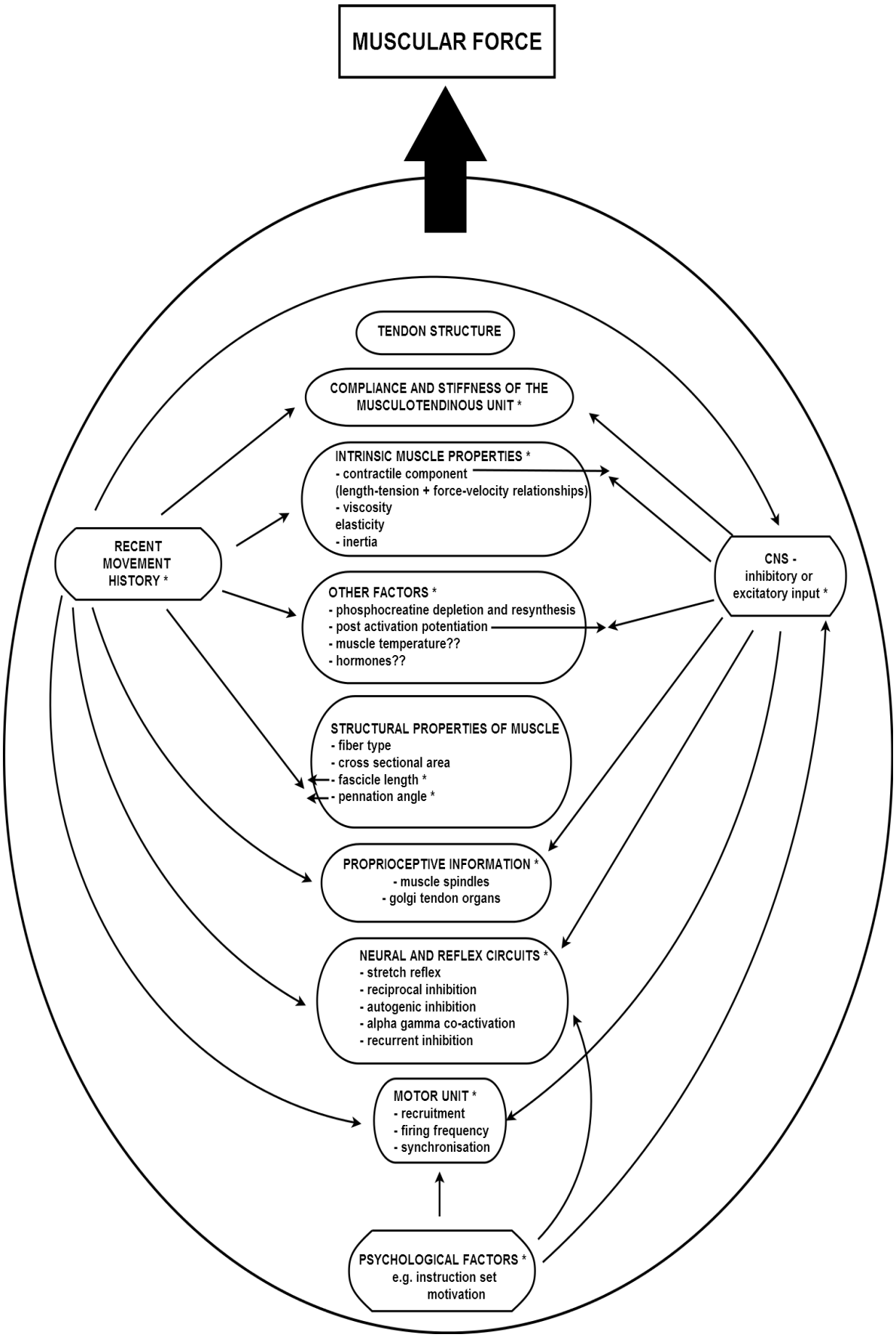


Figure 2. Factors that can influence muscular force production

2.3 Model of the musculotendinous unit

The model of the musculotendinous unit provides an overview of factors that have an influence on force production. Gottlieb (1996) proposes a more complex musculotendinous model (figure 3) based on that hypothesised by Hill (1970). The model includes the CNS, intrinsic properties of the muscle and tendon, reflex arcs and neural impulses. Inertia is also represented in the model as M_{limb}, and is the tendency of a body to resist any change in its state of motion or rest (Hall, 2003). Gottlieb's (1996) model reflects the interactive nature of the neuromuscular system, in particular how force is developed, transferred and regulated.

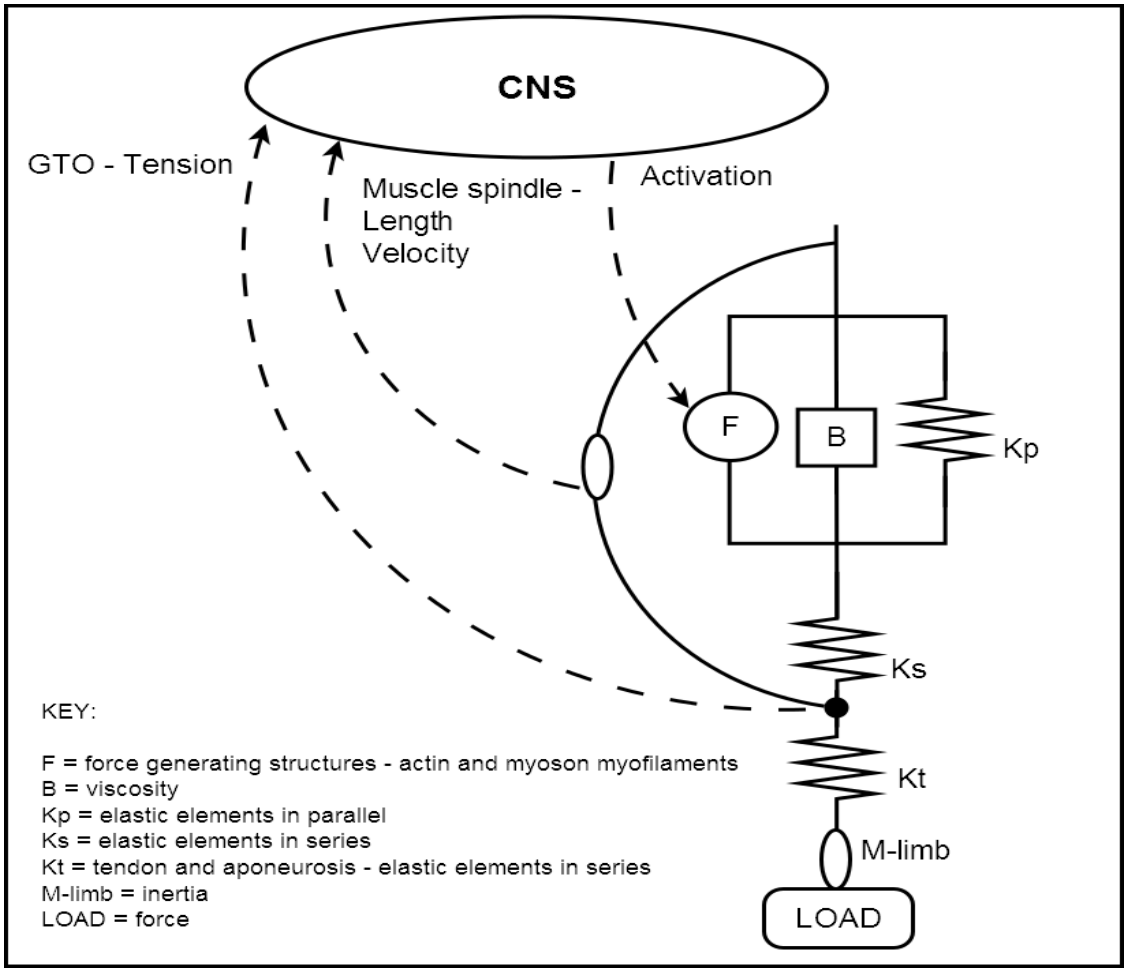


Figure 3. Model of the musculotendinous unit

2.4 Recent movement history

The contractile response and force produced by skeletal muscle is determined by its recent movement history (Chapman, 1985). That is, the previous active and passive movement of skeletal muscle, which affects the torque-angle curve produced during subsequent contractions. The contractile process and properties of skeletal muscle might be impaired or enhanced by previous movements, leading to an increase or decrease in force (Chapman, 1985). The level of force produced during any ensuing human movement is dependent on the type, frequency, duration, intensity and velocity of the preceding muscular contraction(s). The movement history of skeletal muscle therefore influences many different factors. Active movement history affects phosphagen energetics, Post-Activation Potentiation (PAP), intrinsic properties and neural components of skeletal muscle. Passive movement history also affects the intrinsic properties of skeletal muscle. Recent movement history clearly differs between grouped and interspersed repetitions of an isokinetic movement. In particular grouped repetitions consist of more work completed over a shorter period of time compared to interspersed repetitions. The rest associated with interspersed repetitions may result in an optimisation of muscle properties and a larger amount of force produced compared to grouped repetitions. As the recent movement history differs between grouped and interspersed repetitions so does the total amount of force produced.

2.5 Central nervous system and motor control

The CNS continuously regulates muscular contractions based upon the somatosensory information it receives. Broadly speakingthe CNS has three levels of motor control which include: the cerebral cortex, the descending systems of the brainstem and the spinal cord (Kandel, Schwartz & Jessell, 1991). Collectively these levels are referred to as the motor system. The motor areas of the cerebral cortex give general commands to other regions of the motor system and their parallel structure allows them to adjust reflexes (Kandel et al., 1991).

The descending systems of the brainstem contain axons that project to and regulate networks in the spinal cord. Their role is to integrate visual, vestibular and somatosensory inputs. The spinal cord controls reflexes and spatiotemporal patterns of muscle activation via neural circuits, spinal interneurons and motor neurons (Kandel et al., 1991). These levels of the motor system are interconnected with sensory information received at each level. This structure allows for an integration of motor commands for the control of muscular force.

Commands from the motor cortex are sent via action potentials down the corticospinal tract to the spinal cord. Action potentials and input to interneurons in the spinal cord are dependent on sensory information such as that from muscles spindles and Golgi tendon organs (Latash, 1998). Action potentials and feedback from proprioceptors is modulated by feedforward processes from higher control centres such as the cerebellum and the basal ganglia, as well as descending axons from the motor cortex (Kandel et al., 1991). Interneurons in the spinal cord such as group 1a and 1b inhibitory interneurons, and Renshaw cells also regulate neural input and output of the spinal cord. These interneurons are also inhibited and excited by higher control centres and descending axons (Kandel et al., 1991). Corticospinal neurons and interneurons connect to alpha and gamma motor neurons allowing the CNS to directly control muscular force. The input and output of action potentials in the spinal cord is modified and influenced by the different feedforward and feedback pathways of the motor and sensory system,. These pathwayscan therefore modulate muscular contractions causing variations in the amount of force produced during human movement.

2.6 Motor units

A motor unit is an alpha motor neuron and all the muscle fibers it innervates, and is the basic unit of motor function (Enoka, 2002). Motor units are classified into three groups based on their contraction speed and resistance to fatigue (Noth, 1992). Type I fibers have a slow contraction speed and are fatigue resistant. Type IIb fibers are fast twitch allowing for a rapid

and high level of force, but they fatigue quickly. Type IIa fibers have intermediate properties of the other two fibers as they produce fast, strong twitches but are somewhat fatigue resistant (Cormie, McGuigan & Newton, 2011).

The CNS varies muscular force based on the recruitment, firing frequency and synchronisation of different motor units. The size principle determines the recruitment of motor units. It states that the recruitment of motor units within a muscle occurs in a systematic order from small motor units to larger ones (Latash, 1998). This recruitment is a reflection of the conduction velocity and axon diameter of the motor neurons (Kandel et al., 1991). Small alpha motor neurons that innervate type I fibers are activated at low force levels. As the force level increases larger alpha motor neurons of type IIa and IIb fibers are activated. The number and type of motor units recruited affects the level of muscular force produced (Cormie et al., 2011).

The firing frequency of motor units represents the regularity of action potentials transmitted from the alpha motor neuron to the muscle fibers. Increasing the firing frequency of a motor unit results in an increase in the magnitude and rate of force during a muscular contraction (Cormie et al., 2011). The ability of the CNS to change the frequency of action potentials to motor units allows it to easily tweak muscular activation and the resulting force. To increase muscular force the CNS can either recruit new motor units and or increase the firing frequency of already recruited motor units (Latash, 1998).

Motor unit synchronisation occurs when two or more motor units are activated concurrently (Cormie et al., 2011). It has been hypothesised that synchronisation augments the magnitude and rate of force production during muscular contractions. It has also been theorised that synchronisation of motor units assists with the co-activation of different muscles to improve the rate of force development (Cormie et al., 2011). Motor units provide an interface between the CNS and skeletal muscle, and their level of excitation determines the

contraction of skeletal muscle and force output. Changes in the firing frequency, recruitment and synchronisation of motor units during repeated muscular contractions will lead to variations in muscular force.

2.7 Intrinsic properties of muscle

2.7.1 Contractile component of skeletal muscle

Two important force generating structures within skeletal muscle are the actin and myosin myofilaments and are represented as F in figure 3. The cross bridge cycling of the myofilaments causes the generation of force (Patel & Lieber, 1997). A muscle's force and velocity potential is affected by the number of sarcomeres in parallel and series respectively (Jones, McCartney & McComas, 1986). The force produced by the myofilaments during cross bridge cycling also depends on the length-tension and force-velocity relationships of skeletal muscle. Neural activation from the CNS controls the cross bridge cycling of the myofilaments and therefore the level of force produced during this process.

2.7.2 Viscosity

Viscosity is a fluid property that contributes to the resistance of skeletal muscle in response to deformation and is represented as B in figure 3. The viscosity of muscle is high at the start of an initial movement as the resting state of the myofilaments are viscid, providing resistance to stretch. As movement occurs, the viscosity of the myofilaments eventually declines and there is less resistance. Muscle viscosity can be thought of using the analogy of golden syrup as it functions like a thick fluid. Initially when stirring golden syrup there is resistance to movement but as the movement continues over time there is less resistance.

As the velocity of a movement increases so does the resistance of the viscous element (Latash, 1998). The viscous element (B), like the elastic elements accommodates for velocity and force changes of the contractile component (Gottlieb, 1996). It opposes the shortening of

the myofilaments by damping and absorbing forces. The behaviour of the viscous element is also dependent on the strength of the muscular contraction. In addition to this, viscosity decreases as repeated muscular contractions occur and as muscle temperature increases. The viscous element helps control and limit force during a given movement.

2.7.3 Elasticity

Elasticity is the ability of a muscle fiber to stretch and return to its resting length once a stretch is removed (Hamill & Knutzen, 2003). Elasticity is represented as Kp, Ks and Kt in Figure 3. Kp are the elastic elements in parallel to muscle and includes muscle membranes, fascia and intramuscular connective tissue. Ks is the elasticity of all elastic elements in series and includes titin, actin and myosin myofilaments, cross bridge stiffness and sarcomere non-uniformity (Knudson, 2003). Kt is the tendon and aponeurosis and accounts for the second series elastic element. This will be discussed in more detail in the next section on tendon structure and function.

The elasticity of the Kp and Ks elements allows them to absorb and store force proportional to the rate of application (Nordin & Frankel, 2001). The elastic recoil of these elements creates a passive pull on the contractile unit causing it to return to its resting length (Oatis, 2004). The elastic elements also provide tensile force proportional to changes in their length during stretching. The Kp and Ks elements allow for an even transmission and release of force during muscular contractions.

Although Ks and Kp elements help keep sarcomeres at a length suited for contraction they do represent ‘elastic slack’ in the musculotendinous unit. When a sarcomere is activated force will not be transmitted through the tendon until the elastic slack is taken up (Handcock, 2003). This phenomenon is referred to as INWASTE (initial wastage of cross bridges) and causes a time delay between the contraction of muscle and the onset of movement (Handcock,

2003). Despite this limitation the elastic elements of the musculotendinous unit still act as a spring to adjust and modify force during muscular contractions.

2.8 Tendon structure and function

The tendon and aponeurosis are integral elastic elements in series with the contractile component and are represented as Kt in figure 3. Tendons are actuators of force and not just rigid links between muscle and bone. They are primarily composed of collagen fibres that form a matrix of cells known as fibrils (Nigg & Walter, 2007). Fibrils have a wave-like crimped appearance that disappears as the tendon is stretched under load. Fibrils are organised into fascicles providing a multilayered structure. Each fibril consists of microfibrils which in turn contain tropocollagen.

Tendons attach to muscle fibers via connective tissue of the aponeurosis, and their attachments on bone can be narrow or wide (Nigg & Walter, 2007). Muscles rarely have tendons at each end and their dimensions can vary in length and breadth. These differences affect the mechanical properties of a tendon with longer tendons having a greater capacity to store elastic energy (Enoka, 2002).

The structural components of tendons and their high collagen content enable them to have a high level of tensile strength, stiffness and resistance when stretched (Higgs & Winter, 2009). As tendons have a high level of stiffness, they show very little hysteresis and deformation. Tendons operate in a non-linear manner as they are compliant at low loads and stiffer at higher loads. The resilience and elasticity of tendons enables them to modify and release energy efficiently to skeletal structures (Hamill & Knutzen, 2003). Therefore tendons have an essential role in the level of force produced during muscular contractions.

2.9 Compliance and stiffness

The production and transmission of force by the musculotendinous unit is largely determined by its level of compliance and stiffness (Enoka, 2002). Stiffness is the resistance of a tissue to deformation, and is the change in load per unit of length displacement (df/dl) (Watkins, 1999). It is the magnitude of force required to change tissue length. The internal structural bonds of the actin and myosin myofilaments, the cytoskeleton and connective tissue cause resistance to lengthening and influence the ability of the musculotendinous unit to develop force (Magnusson, 1998). The initial level of resistance and its steady decline during a stretch is referred to as Short Range Elastic Stiffness (SRES). This phenomenon is largely due to the springlike properties of actin-myosin bonds (Enoka, 2002).

Tissues with a high level of stiffness display less deformation in response to a given load and are more resilient to stretching (Hall, 2003). The rate of stretch or load affects the stiffness and compliance of the musculotendinous unit. For example, if the unit is stretched at a fast rate, this will increase its passive resistance and stiffness. Whereas, if a stretch occurs at a slow rate, there will be a small increase in passive resistance and a high level of compliance.

Compliance is the deformation of a tissue to resistance, and is the change in length displacement per unit of load (dl/df) (Watkins, 1999). It is how much the length of the tissue changes for the amount of force applied. The greater the deformation produced by a given amount of load, the more compliant the tissue. Increasing the compliance of a tissue decreases its stiffness and vice versa (Watkins, 1999). A musculotendinous unit that displays a greater level of stiffness has an enhanced ability to transfer force (Wilson, Elliott & Wood, 1992; Bojsen-Moller, Magnusson, Rasmussen, Kjaer & Aagaard, 2005), while a high level of compliance allows musculotendinous units to have a better capability to absorb and store force (Wilson et al., 1992). The level of compliance and stiffness of the musculotendinous unit affects the amount of force it is able to generate and transfer to skeletal structures.

The stiffness and compliance of the musculotendinous unit is controlled by intrinsic factors, neural mechanisms and muscular factors (Brownstein, 1997). Intrinsic mechanisms relate to the internal structures of musculotendinous unit and are dependent on the level of muscle activation and recent movement history. Muscular factors that determine stiffness and compliance include the frequency of muscle activation, muscle fiber recruitment, sarcomere length-tension and force velocity relations, and muscle architecture (Lieber & Friden, 1992). Neural mechanisms that regulate musculotendinous stiffness and compliance include heterogenic reflexes, the stretch reflex and reciprocal inhibition, and autogenic inhibition (Brownstein, 1997). Therefore, the regulation of the stiffness and compliance of the musculotendinous unit affects its force output. Changes to the stiffness and compliance of the musculotendinous unit during repeated muscular contractions will ultimately lead to variations in the amount of force produced.

2.10 Proprioceptors, neural circuits and reflex arcs

Length and force sensitive reflexes are also represented in figure 3. The CNS effectively controls muscular force by receiving sensory information from muscle spindles and Golgi Tendon Organs (GTO's). Muscle spindles are located within the muscle belly and are parallel to muscle fibers. They provide information about length and velocity changes of muscle, and form the basis of the stretch reflex (Latash, 1998).

When a muscle lengthens the spindles are stretched and impulses are sent down its 1a afferent axon to alpha motor neurons in the spinal cord (Kandel et al., 1991). The activation of the alpha motor neuron causes the muscle and its synergists to contract. This in turn decreases the stretch on the muscle spindles. Firing of the afferent axon also activates the 1a inhibitory interneuron which inhibits antagonist muscles (Kandel et al., 1991). The contraction of the agonist muscle and relaxation of the antagonist muscle is referred to as reciprocal inhibition,

and presumably allows for a greater production of force. It is important to note that the stretch reflex is not invoked with the lengthening of every muscle.

GTO's are located near myotendinous junctions and are in series with skeletal muscle fibers (Kandel et al., 1991). Their role is to detect and monitor the amount of force developed in a muscle. As a muscle contracts, the GTO is deformed (Kandel et al., 1991), and when this is above a certain threshold, a signal travels along its Group 1b afferent axon to the 1b inhibitory interneuron in the spinal cord (Enoka, 2002). This interneuron inhibits agonist and synergist muscles, resulting in a decreased level of force in these muscles.

Activation of the Group 1b afferent axon also excites antagonist and non contracting muscles (Enoka, 2002). This process is referred to as non-reciprocal inhibition or autogenic inhibition. The main function of GTO's is to act as a protective mechanism to help prevent excessive force during muscular contractions (Powers & Howley, 2001). The processes of autogenic and reciprocal inhibition help regulate the amount force generated by agonist and antagonist muscles.

Descending pathways from the cerebral cortex and other higher brain centres provide inhibitory and excitatory input to the 1a and 1b inhibitory interneurons, and motor neurons (Kandel et al., 1991). This allows the CNS to regulate reciprocal and autogenic inhibition, and therefore control the amount of force developed by agonist and antagonist muscles. The CNS also causes a shift from reciprocal inhibition to co-contraction of agonist and antagonist muscles by increasing inhibitory signals to the 1a inhibitory interneuron (Kandel et al., 1991). This shift changes the force output of the agonist and antagonist muscles.

The CNS also controls the strength of the stretch reflex via the fusimotor system (Kandel et al., 1991). The fusimotor system consists of muscle spindles and gamma motoneurons. Gamma motor neurons innervate the intrafusal fibers of muscle spindles and regulate their ability to contract and maintain tension (Latash, 1998). During muscular contractions the

extrafusal muscle fibers shorten causing a slackening of the intrafusal fibers. Gamma motoneurons are coactivated causing an increase in the tension of the intrafusal muscle fibers, which is also paralleled in the extrafusal muscle fiber. This process is referred to as alpha-gamma coactivation. The CNS controls the stretch sensitivity and length of muscle spindles, and their afferent input during muscular contractions. Therefore, by controlling these features of the muscle spindle the CNS has another way in which it regulates muscular force.

Reflex arcs are also controlled by recurrent inhibition. This involves a local reflex loop of collateral axons and a specialised interneuron known as the Renshaw cell (Enoka, 2002). Action potentials sent from collaterals of the alpha motor neuron and the supraspinal area of the CNS activate the Renshaw cell. As a result it generates inhibitory signals to the same motor neurons, gamma motor neurons and the 1a inhibitory interneuron (Enoka, 2002). These inhibitory signals allow it to modulate the input and output of the whole myotatic unit. The CNS via Renshaw cells regulates large or small transient changes in motor neuron firing by maintaining the firing within certain limits (Kandel et al., 1991). As a result of its effects, recurrent inhibition is another process that helps regulate force production.

Muscle spindles and GTO's are transducers of neural signals and the sensory information they send reaches all levels of the CNS. The CNS modulates and regulates muscular force in many different ways by co-ordinating various reflexive pathways and interneurons. The proprioceptors, reflexive pathways and the CNS all work as one to control the musculotendinous unit and the level of force it produces.

2.11 Phosphocreatine depletion and resynthesis

Adenosine triphosphate (ATP) and phosphocreatine (PCr) are high energy compounds stored in skeletal muscle, and play an integral role in muscular contractions and force generation. During short term high intensity exercise PCr is used as a primary fuel source for ATP replenishment. PCr can be depleted to 35 - 55% of its resting stores after 6-s of maximal

sprinting and after 10 - 12.5-s is depleted to approximately 40 - 70% (Spencer, Bishop, Dawson & Goodman, 2005). The breakdown of PCr is dependent on the intensity of the muscular contraction and as it is stored in small amounts it depletes very quickly. The decline of PCr during high intensity exercise results in a decrease of force (McMahon & Jenkins, 2002).

As PCr reserves decline there is more reliance on the glycolytic energy system for the replenishment of ATP. The increase of H^+ during high intensity exercise results in muscular fatigue and a decrease of force (McMahon & Jenkins, 2002). The greater the degradation of PCr, the greater the time required for its repletion, as resynthesis must start from a lower level (McMahon & Jenkins, 2002). The resynthesis rate of PCr after complete degradation follows a saturation curve, with the time to resynthesise 50% of its resting store reported between 21 – 57-s (Spencer et al., 2005). Complete resynthesis of PCr may occur within 8 min (Baechle & Earle, 2000). However, the time course of PCr resynthesis depends not only on the extent of PCr depleted but also the type of exercise performed, its intensity, duration and the number of exercise bouts completed (Maughan & Gleeson, 2004). The ability to produce high power outputs is directly related to the resynthesis of PCr (Bogdanis, Nevill, Boobis, & Lakomy, 1996).

In order to maximise force production during repeated bouts of high intensity exercise sufficient rest periods should be given for PCr repletion. Guidelines for exercise to rest period ratios to use PCr as the primary fuel source and resynthesis thereof include 1:12 to 1:20 (Baechle & Earle, 2000). Therefore depletion and recovery of PCr is important during intermittent exercise as it dictates force production and metabolic fatigue. The consecutive nature of grouped isokinetic repetitions and the metabolic fatigue likely to accumulate within a set of five maximal repetitions may result in a reduced PCr availability and a decline of peak torque (McMahon & Jenkins, 2002). In contrast the rest associated with interspersed isokinetic

repetitions may allow for sufficient replenishment of PCr and an increase of peak torque McMahon & Jenkins, 2002).

2.12 Pennation angle and fascicle length

Fascicle length and pennation angle both influence force production. An increase in muscle fiber length increases the muscle's ability to generate force at a given shortening velocity (Lieber & Friden, 1992). An increased muscle fiber length may result in the muscle fiber being at a more optimal length (LaRoche, Lussier & Roy, 2008). This length is characterised by an increased number of actin-myosin cross bridges allowing for a larger degree of myofilament overlap (Handel, Horstmann, Dickhuth & Gulch, 1997), and a greater level of tension (Widmaier, Raff & Strang, 2006). Both the increased number of sarcomeres and the increased muscle fiber length results in a right shift of the force-velocity curve causing an increased maximum force and velocity of the muscle.

Pennation angle of a muscle is the angle between the muscle's fascicles and the line of action between the origin and insertion (Cormie et al., 2011). An increased pennation angle means muscle fibers are at a greater angle in relation to the tendon (Baechle & Earle, 2000). As a result more sarcomeres can be arranged in parallel, and thus more contractile tissue can attach to the tendon (Cormie et al., 2011). A muscle's force potential is proportional to the number of active sarcomeres in parallel (Jones et al., 1986). So the greater number of sarcomeres in parallel (from an increased pennation angle) results in an increase of muscular force.

The increase of force from a greater pennation angle may also be due to the effect that fascicle angle has on tendon excursion (Blazevich, 2006). Fibres of pennate muscles rotate as they shorten so tendon displacement is greater than the shortening distance of individual fibres (Cormie et al., 2011). Fibres that shorten less for a given tendon displacement are more likely to operate closer to their optimum length, thus allowing for an increase of force (Blazevich,

2006). However, there is a trade off between pennation angle and the proportion of force directed along the tendon. When pennation angle is greater than 25° less force is directed along the tendon, but this effect is minimal when fascicle angle is from 0° - 25° (Blazevich, 2006).

The majority of research investigating muscle architecture during and after exercise has shown that pennation angle increases and fascicle length decreases (Csapo, Alegre & Baron, 2011; Mademli & Arampatzis, 2005; Brancaccio, Limongelli, D'Aponte, Narici & Maffulli, 2008; Ishikawa et al., 2006). Although some studies have shown an increase in fascicle length and a decrease or no change in pennation angle after exercise (Ishikawa et al., 2006; Mahlfeld, Franke & Awiszus, 2004; Storey, Wong, Smith & Marshall, 2012). These inconsistent findings for changes in pennation angle and fascicle length during and after exercise is reflective of the varied exercise modes, intensities, volumes, muscle groups and contraction types used in the studies cited above. Although it does seem that exercises of a high volume and an exhaustive nature might be stimuli for changes in pennation angle or fascicle length (Csapo et al., 2011; Mademli & Arampatzis, 2005; Brancaccio et al., 2008; Ishikawa et al., 2006). As pennation angle and fascicle length may not immediately return to their original state after exercise, such behaviour also reflects the transient nature and plasticity of the musculotendinous unit. Therefore variations in pennation angle and fascicle length may lead to fluctuations in the level of muscular force produced during exercise. The extent of this effect during and after isokinetic exercise has yet to be determined and future research is needed in this area.

2.13 Muscle temperature

Exercise causes skeletal muscle to generate heat, which results in an increase of muscle temperature (Tm) in proportion to the relative exercise workload (Saltin, Gagge & Stolwijk, 1968). During isokinetic exercise Tm increases, however, the extent of this Tm increase and its effect on peak torque or angle of peak torque has yet to be researched. Furthermore,

changes of Tm during rest periods of isokinetic exercise and the impact this has on peak torque or angle of peak torque is also unexplored. An increase of Tm may have a limited effect on peak torque during isokinetic exercise, as evidenced by studies examining muscle warming prior to isokinetic exercise. The majority of studies investigating the effect of muscle warming on isokinetic peak torque have shown that peak torque does not increase with muscle warming (Dewhurst et al., 2010; Cheung & Sleivert, 2004; Racinais et al., 2006). Only one study has shown that isokinetic peak torque increases with an increase of muscle temperature (Bergh & Ekblom, 1979). These equivocal results could be due to the differences in the methods and time used to warm the tested musculature. The inconclusive results could also be due to the exercise tests performed prior to the isokinetic task.

Increasing muscle temperature prior to exercise seems to have a beneficial effect on peak force during longer duration activities that require more musculature such as a 6-s or 20-s maximal cycle sprint (Sargeant, 1987; Gray, De Vito, Nimmo, Farina & Ferguson, 2006). An increase in Tm prior to isokinetic contractions may have no or little effect on isokinetic peak torque due to the short and intermittent nature of the task. Further research needs to be conducted in order to determine whether Tm increases with isokinetic exercise particularly after interspersed or grouped repetitions, and whether a prior increase in Tm affects isokinetic peak torque or angle of peak torque.

2.14 Post-Activation Potentiation

PAP) is another factor that changes acutely and affects force production during maximal repetitions. PAP refers to the acute increase in the performance characteristics of skeletal muscle as a result of their contractile history (Tillin & Bishop, 2009). PAP normally consists of an initial conditioning contraction(s), followed by a recovery period and the performance of a subsequent activity (Sale, 2002). The conditioning contraction used to induce PAP is often a sustained or series of maximal voluntary contractions. These conditioning contraction(s) may

facilitate an increase in the force output or rate of force development of the subsequent activity (Sale, 2002).

Three different mechanisms have been proposed to be responsible for the occurrence of PAP which includes: (i) the phosphorylation of myosin regulatory light chains, (ii) an increase in the recruitment of higher order motor units, and (iii) acute changes in the pennation angle of skeletal muscle (Tillin & Bishop, 2009). It is important to note that the literature of PAP focuses on these three mechanisms and seems to ignore the effects of other muscle properties such as those outlined in this review. Further research needs to investigate all possible mechanisms responsible for causing PAP and the main contributors thereof. The extent to which the mechanisms of PAP are activated depends on the frequency, intensity, duration, and the type of conditioning contraction(s). In addition to this, PAP is affected by the recovery period following the conditioning contraction and the type of subsequent activity performed. Following an intense or prolonged conditioning contraction(s) PAP will increase significantly but so will fatigue. A longer recovery period after the conditioning contraction results in a greater recovery from fatigue, but also causes a greater decline of PAP (Sale, 2002). Optimal muscular performance occurs when fatigue has subsided but potentiation still exists (Hodgson, Docherty & Robbins, 2005).

There is limited research on the effects of PAP during isokinetic exercise. The effect of PAP on a subsequent isokinetic knee extension task was studied by Batista et al. (2007). The conditioning contractions involved 10 maximal isokinetic knee extensions at 60°/s interspersed with a 30-s rest period, with separate test days allocated for each rest interval. Peak torque during three consecutive isokinetic knee extensions at 60°/s increased significantly at intervals of 4, 6, 8, 10 and 12 min after the conditioning contraction.

Chaouachi et al. (2011) observed slightly different results when they investigated the effects of PAP following 10 isokinetic conditioning contractions of reciprocal knee extension

and flexion at 60°/s or 300°/s. Two to five minutes after the conditioning contraction participants performed three isokinetic knee flexion and extension contractions at 60°/s and 300°/s. Peak torque of the knee extensors and flexors at 300°/s was only potentiated by the 300°/s conditioning contraction, with increases between 6% - 8% after 2 min of recovery. By contrast, the 60°/s conditioning contraction produced no potentiation for both speeds and muscle groups. These results suggest that there might be a velocity component to the conditioning contractions used.

The varied results between the studies by Chaouachi et al. (2011) and Batista et al. (2007) is a reflection of the different volumes, types and velocities of the conditioning contractions. Interspersed repetitions and the rest associated with them may optimise PAP and thus cause an increase in peak torque. Future research is needed within the area of PAP and isokinetic exercise, particularly how different velocities and conditioning contractions affect peak torque, although from these two studies it does seem that PAP increases peak torque.

2.15 Section summary

Force production is a very complex and dynamic process as a multitude of factors control and affect the level of force produced during muscular contractions. During repeated muscular contractions some of these factors may change, optimise and stabilise at different magnitudes and rates which may result in variations of force. Factors that affect force production during muscular contractions include movement history, action potentials from the CNS, neural circuits and reflex arcs, feedback from muscle spindles and GTOs, motor unit excitation, intrinsic and structural properties of the musculotendinous unit, stiffness and compliance, phosphocreatine concentrations and post-activation potentiation. Changes of pennation angle and fascicle length, muscle temperature and hormones during isokinetic dynamometry and their effect on peak torque and its angle have yet to be clearly determined and further investigation is needed.

Processes of reciprocal inhibition, autogenic inhibition, alpha-gamma co-activation and recurrent inhibition all determine muscular activation and force. The motor systems of the CNS regulate the contraction and relaxation of skeletal muscle by changing the input and output of action potentials in the spinal cord. Higher control centres and descending pathways provide inhibitory and excitatory input to interneurons and motor neurons which alter reciprocal inhibition, autogenic inhibition, co-contraction of muscle and recurrent inhibition. The CNS also controls muscular contraction and force by determining the excitation of motor units.

Although the CNS largely overrides neural circuits and reflex arcs that influence force production via action potentials, other properties of the musculotendinous unit also have a key role in altering force production. The stiffness and compliance of the musculotendinous unit significantly affects its force production. Musculotendinous units with a high level of stiffness are better able to transfer force, whereas a high level of compliance allows for greater force absorption. These properties are controlled by intrinsic, neural and muscular factors. Intrinsic properties of muscle act as a filtering mechanism of muscular force whereby the transfer of force is dependent on a muscle's level of viscosity and elasticity.

It is important to note that during isokinetic knee extension the limbs are not in contact with the ground so it is a very different movement physiologically compared to functional movements such as walking, backward to forward to stepping or running. Compared to these functional movements a different proprioceptive response, feedback and modulation of sensory information may occur during isokinetic knee extension as less external stimuli is available to the sensory system. Due to the physiological nature of isokinetic knee extension some factors influencing force production such as processes of the stretch reflex, GTOs and alpha-gamma coactivation might be limited during such a task.

Current isokinetic strength testing literature assumes that torque production and that force output from one movement to another is constant (Brown, 2000; Chan et al., 1996; Brockett et

al. 1999; Brockett et al. 2001),. However, as this review highlights, torque production is a dynamic process and there are numerous factors that affect peak torque and angle of peak torque. Factors of force production outlined in this review form the basis of the observed biological variability of force during maximal isokinetic contractions. Specifically, these factors may affect the consistency and the within-subject variation of peak torque and angle of peak torque during muscular contractions. Not only is the behaviour of peak torque and angle of peak torque over multiple interspersed and grouped repetitions unknown, the exact mechanism(s) contributing to this behaviour is also unknown. These phenomena may always have large fluctuations or they may eventually stabilise and become consistent over multiple repetitions. Providing a rest of 30 or 60-s between repetitions may also result in an optimisation of muscle properties and consequently peak torque or angle of peak torque may also optimise. The rest period associated with interspersed repetitions during isokinetic strength testing considers factors such as phosphocreatine resynthesis, post-activation potentiation and recent movement history. Such rest periods may lower the within-subject variation of peak torque and angle of peak torque, and increase the magnitude of peak torque.

The next section of the review will cover: (i) the possible significance of angle of peak torque, (ii) measures of reliability used in isokinetic dynamometry, and (iii) reliability studies of peak torque and angle of peak torque during isokinetic concentric knee extension.

2.16 Possible significance of angle of peak torque

2.16.1 Theory of angle of peak torque

Angle of peak torque is the joint angle of a given movement at which maximum torque is produced, and is also referred to as optimum torque angle (Brockett et al., 2001). Angle of peak torque is speculated to be an important measure as it may indicate the potential risk of muscular injury (Brockett et al., 2001; Bemben & Johnson, 1993). It has been hypothesised that if angle of peak torque occurs towards the end range of a concentric movement (at a shorter muscle length) for an agonist muscle, the greater the range of motion through which the muscle is relatively weak, increasing its susceptibility to exercise-induced muscle damage, muscular tears and strains (Pull & Ranson, 2007; Brockett, Morgan and Proske, 2004). For example, during knee extension if the angle of peak torque occurs at the end range of the movement, say at 40° of flexion, the quadriceps muscle might be weaker and more susceptible to injury compared to angle of peak torque occurring earlier in the movement (e.g. 80°).

It is believed that if the angle of peak torque occurs towards the beginning of a concentric action (or longer muscle lengths) the contractile properties of the muscle are at an advantage as the descending limb of the length-tension curve is reduced (Brockett et al., 2001). The descending limb is where sarcomeres are suggested to be stretched beyond their optimum length. This area is thought to be associated with weaker sarcomeres and inhomogeneities in the lengthening of sarcomeres (Proske & Morgan, 2001), both of which are thought to cause micro-tears of the muscle which may in turn lead to muscle strain injuries (Brockett et al., 2001). The potential for damage in a muscle may depend on where angle of peak torque occurs during a given movement, as if it occurs at the beginning of a concentric action (or

longer muscle length) the muscle might be more protected against injury (Brockett et al., 2004).

It should be noted that this hypothesis is based on measuring angle of peak torque during concentric contractions rather than during eccentric contractions. Based on this theory measuring angle of peak torque has potential implications for understanding injury mechanisms. For example it could be used to establish whether an individual is at greater risk of muscular injury and whether the tested muscle group lacks strength in a certain range of motion. Angle of peak torque could be used to distinguish between previously injured and uninjured muscle groups, and possibly predict whether muscular injury may occur (Brockett et al., 2004). In summary angle of peak torque may indicate the condition of the muscle and its ability to function, and could be a useful diagnostic tool to inform training or rehabilitative programmes.

In terms of performance measuring angle of peak torque could allow practitioners to know when optimum force production occurs during a given movement. This may provide more insights into how angle of peak torque affects athletic performance, particularly the biomechanics, kinetics and kinematics of a given movement. Angle of peak torque may also be used as a measure to determine whether changes have occurred to the torque-angle relationship from exercise or rehabilitative programmes. Changes in the angle of peak torque may also occur as the musculotendinous unit gets stronger or as it repairs from injury. It should also be noted that most research has focused on the angle of peak torque for the knee flexors. The significance of angle of peak torque for the knee extensors could be different to the knee flexors, as the knee extensors have a different function and structure.

Angle of peak torque is assumed to be an indicator of optimum muscle length and overlap of the actin and myosin myofilaments. Due to this assumption changes in the degrees of angle of peak torque are thought to occur mainly due to changes in the overlap between the

actin and myosin filaments. Therefore the torque-angle relationship is often assumed to represent sarcomere length, with torque-angle measures indirectly measuring the length-tension relationship of the sarcomere as inferred by Brockett et al. (2001). Whether angle of peak torque represents optimum muscle length as proposed in the studies performed by Brockett et al. (2001; 2004) is questionable.

Firstly the length-tension and torque-angle relationships differ in how they are measured. The length-tension relationship involves the isometric measurement of a single muscle fiber or a whole muscle via a tensiometer. Whereas the torque-angle relationship is measured on an isokinetic dynamometer at a single joint level. At a single joint level properties of muscle such as neural factors, compliance and stiffness of the musculotendinous unit, viscosity and elasticity, affect force production and the angle of peak torque in a movement. At a sarcomere or single muscle fiber level neural factors are nonexistent and other properties may differ, so the optimum length of the sarcomere may not coincide with angle of peak torque of the torque-angle relationship.

Studies such as those by Brockett et al. (2001; 2004) assume that the contractile element of muscle is the only factor that accounts for angle of peak torque, however this is obviously not the case as other properties of muscle have a very significant role. Enoka (2002) notes that changes in whole muscle length, which includes muscle fibers and tendon, does not necessarily coincide with the change in length experienced by the muscle fibers. Furthermore, the length-tension relationship of a single muscle fiber does not describe the force exerted by a muscle during movement (Enoka, 2002). These differences between the length-tension and torque-angle relationships should be acknowledged if comparisons are to be made between the two relationships.

2.16.2 Reliability issues with angle of peak torque

Despite the possible benefits of measuring angle of peak torque outlined above, there are issues with the reliability of the measure. Brockett et al. (2001) measured angle of peak torque of the knee flexors before and after an acute bout of eccentric exercise. They found that angle of peak torque shifted in the direction of longer muscle lengths by up to 11° three days after the first eccentric exercise, with further increases in angle of peak torque after a second bout of eccentric exercise eight days after the first. These results led them to conclude that the sustained shift in angle of peak torque is a protective strategy against injury from eccentric exercise, and that angle of peak torque could be a useful measure for potential injury. Further to this they note that the initial change in angle of peak torque is due to a disruption of sarcomeres which cause an increase in the muscles series compliance, and that the sustained shift in angle of peak torque is due to an increase in the number of sarcomeres in series. This study is based on a preliminary study of the knee flexors at an angular velocity of 60°/s, that suggested that torque-angle curves can be reliably generated (Brockett et al., 1999). However, this study consisted of only three participants and did not use any statistical analysis. The preliminary study also noted that two animal models were used to verify the reliability of the torque-angle and length-tension relationships of the knee flexors. Again this provides no evidence for the reliability of angle of peak torque during isokinetic contractions.

The methods outlined in the Brockett et al. (1999) reliability study are not clear and do not provide evidence for the actual reliability of angle of peak torque. The authors do not provide SEM or any other measures of reliability for angle of peak torque during isokinetic contractions of the knee flexors. As the reliability of angle of peak torque was not established the results of the study by Brockett et al. (2001) are questionable. This is a major reason why the significance of angle of peak torque is only hypothetical. Other studies investigating angle of peak torque (e.g. Brockett et al., 2004; Bowers, Morgan and Proske, 2004; Brughelli, Cronin

and Nosaka, 2010a; Brughelli et al., 2010b) base the reliability of this measure on the questionable reliability study performed by Brockett et al. (1999). These studies also did not account for the magnitude of the standard error of measurement of angle of peak torque.

Studies conducted by Mackey, O'Sullivan, O'Connor and Clifford (2011) and Koller, Sumann, Leichtfried and Schobersberger (2008) measured changes in angle of peak torque, however both of these studies cite reliability studies which did not measure angle of peak torque. Philippou, Bogdanis, Nevil and Maridaki (2004) cited Brockett et al. (2001) stating that torque-angle curves are a reliable measure of muscle damage even though the study by Brockett et al. (2001) was not a reliability study. Additionally, Cramer et al. (2006; 2007) measured changes in angle of peak torque before and after an acute bout of stretching, but they did not cite any reliability studies for angle of peak torque. Yeung and Yeung (2008) measured changes in angle of peak torque after an eccentric stepping task, and reported their own preliminary test-retest reliability study for angle of peak torque. A slight fault of this study was that they only reported an Intraclass Correlation Coefficient (ICC) for angle of peak torque and not a SEM. As they did not report the SEM of angle of peak torque, the magnitude of error actually associated with this measure is unknown, but at least they did perform a more robust test-retest reliability study for angle of peak torque compared to those studies above.

The validity of the results and the measures of angle of peak torque within these studies are therefore problematic as the changes in angle of peak torque may just represent measurement error. As SEM has not typically been reported the ability to accurately track and quantify true changes in angle of peak torque is reduced. All of the above studies investigating angle of peak torque have used dynamometer angle to infer measures of true knee joint angle. These studies have not acknowledged that there is a difference between these two angles and have ignored or not considered possible measurement errors when using dynamometer angle to infer measures of true knee joint angle.

The research presented by Brockett et al. (1999; 2001) form the foundation and core of the angle of peak torque literature. Many studies have cited the preliminary reliability study conducted by Brockett et al. (1999) but they have not critically examined the methods and results of this study. The current research outlined above on angle of peak torque assumes that it is a consistent and reliable phenomenon without any rigorous scientific investigation. As the results of this preliminary reliability study are unknown the whole theory, significance and reliability of angle of peak torque is brought into question. Establishing the reliability and the SEM of angle of peak torque will help determine whether further research should be performed in this area. If such research went ahead it may highlight the exact significance and importance of angle of peak torque. Previous and current reliability studies of angle of peak torque will be outlined in the last section of the review.

2.17 Different measures of reliability

Reliability is the reproducibility or consistency of a measure and is a reflection of its precision (Hopkins, 2000). Within-subject variation is the most important measure of reliability as it affects the magnitude of change required in a measure (e.g. peak torque) in an experimental study (Hopkins, 2000). For example if the within-subject variation of angle of peak torque is unknown prior to testing the magnitude of measurement error associated with it is also unknown, and consequently true changes in this measure cannot be determined. Establishing the within-subject variation of a measure enables any changes of it within or between tests to be accurately tracked over time, otherwise if within-subject variation of a measure is unknown prior to testing any changes detected between tests are meaningless.

Standard Error of Measurement (SEM) is a form of within-subject variation and provides an estimate of how much measurement error is associated with a given measure (Safrit & Wood, 1989). In order for a measure to be clinically useful it must have a small level of measurement error associated with it, so that true changes or the effects of an intervention can

easily be detected (Hopkins, 2000). Minimal Detectable Change (MDC) is the smallest amount of change required in a measure in order to detect a true change (Steffen & Seney, 2010). Scores at or above the level of MDC are not confounded by measurement error and reflect a participants' improvement on the test (Steffen & Seney, 2010). MDC is sometimes referred to as the smallest real difference.

So what defines whether peak torque or angle of peak torque have a reliable SEM and an acceptable MDC? Within isokinetic reliability studies peak torque has been noted to be reliable during concentric knee extension if its SEM is less than 12 N.m and its SEM as a percentage of the group mean (SEM%) is less than 8% (Sole et al., 2007). Pincivero, Lephart and Karunakata (1997) note that if the SEM% of peak torque is 5% and 8%, it is low and moderate respectively. Further to this it has been noted that if the SEM of peak torque is less than 8 N.m it is low and if its SEM% is at 15% it is moderate (Hartmann, Knols, Murer & de Bruin, 2009). Sole et al. (2007) also imply that a MDC less than 34 N.m and a MDC as percentage of the group mean (MDC%) less than 20% is acceptable. Impellizzeri et al. (2008) states that an MDC between 12 and 13% is moderate. Notably, these studies investigated the between-session reliability of peak torque. The slight differences in these criteria highlight that there are not accepted guidelines for what is deemed a low, moderate or high SEM of peak torque. Harding, Black, Bruulsema, Maxwell and Stratford (1988) is the only study that outlines the SEM and 95% confidence interval of angle of peak torque with it being 3° and 7° respectively.

Despite the criteria of a reliable SEM and acceptable MDC both of these statistics are still governed by the magnitude of change or difference between measurements, such as from an acute or chronic intervention, or the difference in strength between limbs. For example, an individual wants to compare the difference in peak torque between their non dominant and dominant limbs. The SEM and MDC of peak torque are high at 25 N.m and 50 N.m respectively, and the peak torque attained for the non dominant limb was 150 N.m. However,

the peak torque attained for the dominant limb was 200 N.m, meaning this is a true difference between limbs that is not confounded by measurement error. Even though SEM and MDC might be high or deemed unreliable in this example, true changes can still be detected if the magnitude or difference between single or repeated measures is above the threshold of SEM and MDC. In reality a high SEM and MDC means that true changes and improvements are less likely to be observed, therefore the criteria of a reliable SEM and acceptable MDC is still important.

Isokinetic peak torque of the knee extensors at 60°/s has been reported to change up to 24 N.m after 9 weeks of knee extensor strength training (Van Roie et al., 2013). In regards to acute interventions affecting peak torque, dynamic stretching of the knee extensors has been shown to increase isokinetic peak torque of the knee extensors at 60°/s by up to 19 N.m (Sekir, Arabaci, Akova & Kadagan, 2010). Angle of peak torque of the knee extensors tested isokinetically at 60°/s has been stated to change to up 16° towards the end range of knee flexion immediately after a prolonged eccentric stepping task (Bowers et al., 2004). It is important to note that the aforementioned studies did not perform nor cite any reliability studies of peak torque and angle of peak torque so it is unknown whether the scores obtained are above the measurement error of the test. Additionally, these studies tested peak torque and its angle over only three to four repetitions.

The values outlined in table 1 are the criteria deemed for a reliable SEM and acceptable MDC for this literature review. Notably, these criteria are only a guideline as the SEM and MDC of peak torque and its angle may vary with the number of repetitions performed during testing. Isokinetic peak torque and angle of peak torque of the knee extensors were deemed within a reliable SEM and an acceptable MDC in this literature review based on: (i) that reported in isokinetic reliability studies (Sole et al., 2007; Hartmann et al., 2009), and (ii)

magnitude changes of peak torque and angle of peak torque from given interventions (Van Roie et al., 2013; Bowers et al., 2004; Batista et al., 2007).

Table 1. Criteria for a reliable Standard Error of Measurement (SEM) and an acceptable Minimal Detectable Change (MDC) of peak torque and angle of peak torque

Measure	SEM	SEM %	MDC	MDC %
Peak torque	≤ 15 N.m	≤ 6	≤ 40 N.m	≤ 18
Angle of peak torque	≤ 5°	≤ 6	≤ 12°	≤ 18

Abbreviations: SEM% = Standard Error of Measurement as a percentage of the group mean; MDC% = Minimal Detectable Change as a percentage of the group mean

Other forms of within-subject variation include Coefficient of Variation (CV) and Limits of Agreement (LOA). Besides within-subject variation the other measure of reliability are retest correlations (Hopkins, 2000). Forms of retest correlations include Pearson correlation coefficients and Intraclass Correlation Coefficients (ICC). A CV between 1% and 5% is deemed as an acceptable level of measurement error (Hopkins, 2012). Further to this Croisier, Malnati, Reichard, Peretz and Dvir (2007) report that a CV for peak torque between 2% and 9% is clinically acceptable. Although there are varied acceptable ranges for the CV of peak torque and angle of peak torque a CV of less than 5% is considered the maximum acceptable criteria in this review. An ICC over 0.90 is considered as high, between 0.80 and 0.90 as moderate and below 0.80 as low (Vincent, 2005). Pearson's correlation coefficients greater than 0.80 are considered to show a high level of reliability (Atkinson & Nevill, 1998). In contrast to within-subject variation, ICCs reveal the between-subject variation of a measure and do not capture how much error there is in a measure from one trial to another for a given individual (Hopkins, 2000). Thus, ICCs do not inform whether true changes have occurred in a measure (Sole et al., 2007).

Reliability of a measure can be determined within or between sessions. Between-session reliability often known as test-retest reliability refers to how closely trials of a given measure

match those equivalent trials in a different session. Within-session reliability refers to how closely trials of a given measure track adjacent trials in a session. It is important to know within-session reliability prior to all forms of testing particularly acute interventions or comparing the strength of injured and non injured limbs, as the error of a measure from one adjacent trial to another needs to be known in order to detect a true change. Reliability of peak torque and angle of peak torque in this review will be based primarily on considering the reported levels of within-subject variation (SEM and CV), and in the absence of these statistics reliability will be based on the ICCs reported.

2.18 Reliability studies of peak torque and angle of peak torque

One assumption of isokinetic testing is that angle of peak torque is a consistent phenomenon and thus has a low within-subject variation or SEM (Brockett et al. 1999; Brockett et al. 2001; Bowers, Morgan and Proske, 2004; Brughelli, Cronin and Nosaka, 2010a; Brughelli et al., 2010b). This subsection of the review will critique different within-session and between-session reliability studies of both peak torque and angle of peak torque during concentric knee extension tested isokinetically. Specifically, it will highlight what is needed for further investigation and therefore unintentionally neglects to comment on the contributions made by the reviewed studies. Table 2 summarises the isokinetic reliability studies of concentric knee extension, wherein all repetitions are maximal. The conclusions within table 2 are the reviewer's opinion for acceptable reliability based on the maximum criteria of SEM, CV, ICCs and Pearson's correlation coefficients. These criteria are outlined in the previous subsection of the review (2.18 Different measures of reliability).

Based on the test protocols employed, the majority of the reliability studies outlined in table 2 show that peak torque during concentric knee extension has very good to high within and between-session reliability across a velocity spectrum (Almosnino et al., 2012; Impellizzeri et al., 2008; Maffiuletti, Bizzini, Desbrosses, Babault & Munzinger, 2007; Sole et

al., 2007; Phillips et al., 2000; Brown et al., 1993; Kilfoil & St Pierre, 1993; Wilhite et al. 1992; Brown et al., 1992; Stratford, Bruulsema, Maxwell, Black & Harding, 1990; Harding et al., 1988). Conversely the results for angle of peak torque are very inconsistent. Only a few studies have shown that angle of peak torque has good within and between-session reliability particularly at 60°/s (Bernard et al., 2012; Maffiuletti et al., 2007; Kilfoil & St Pierre, 1993; Harding et al., 1988). Nonetheless the majority of the studies reviewed show that the within and between-session reliability of angle of peak torque is poor (Ayala et al., 2012; Phillips et al., 2000; Bemben & Johnson, 1993; Brown et al., 1993; Wilhite et al., 1992). Due to the mixed findings of these studies for the reliability of angle of peak torque, further investigation needs to be undertaken to determine its within-subject variation.

There are many factors within the reviewed reliability studies (table 2) that are problematic and could ultimately affect the within-subject variation associated with peak torque and angle of peak torque. Firstly, the reviewed studies performed only two to six repetitions of concentric knee extension, most of which were grouped repetitions with no rest period between them. Isokinetic strength testing studies note that maximum torque is typically achieved within two to six grouped repetitions (Baltzopoulos & Brodie, 1989; Brown & Weir, 2001; Johnson & Siegel, 1978; Sawhill, Bates, Osternig & Hamill, 1982). But are maximum torque and a lower SEM really achieved by performing this type and range of repetitions?

During maximal grouped repetitions metabolic fatigue occurs and muscle properties are not fully optimised, as well as this PAP is limited. These factors possibly result in a more variable and lower peak torque output during grouped repetitions compared to interspersed repetitions. Stratford et al. (1990) found that mean peak torque during concentric contractions of isokinetic knee extension at 60°/s was 5% lower when five grouped repetitions were performed compared to interspersed repetitions with a 30-s rest. They also found that interspersed repetitions had a lower SEM for peak torque. Further to this Pincivero, Lephart

and Karunakara (1998) note that rest periods are critical for improving the reliability of peak torque. Harding et al. (1988) also had a 30-s rest between six repetitions of isokinetic knee extension and found a low SEM for angle of peak torque. Some reliability studies (Phillips et al., 2000; Capranica, Battenti, Demarie, & Figura, 1998; Brown et al., 1992; Brown et al., 1993; Wilhite et al., 1992) did not provide a rest between repetitions which may have weakened the reliability of peak torque or angle of peak torque. Although studies by Ayala et al. (2012) and Bemben and Johnson (1993) reported a poor reliability of angle of peak torque when they had a 30-s rest between repetitions. Therefore interspersed repetitions and rest periods during isokinetic strength testing might be important for maximising peak torque and may possibly reduce the SEM of peak torque and its angle. This is of particular importance for angle of peak torque as its reliability is still unclear.

The primary goal of isokinetic strength testing is to reduce within-subject variation as much as possible so an individual's true measurement score is revealed. Another goal of testing is to maximise torque production. Performing only five interspersed repetitions within a test protocol means that maximum peak torque is not achieved. More than five interspersed repetitions need to be performed in order to attain maximum peak torque as muscle properties may take many repetitions to optimise. Completing more than five interspersed repetitions may also improve the SEM associated with peak torque and its angle.

Although maximum peak torque should be attained within an isokinetic testing session the number of repetitions completed should also be practical and time efficient based on the magnitude of difference expected between tests and the SEM associated with the measure. Isokinetic dynamometry has primarily been used as a clinical tool rather than within research or training settings. Clinicians normally observe a large difference in peak torque for an injured limb tested before and after rehabilitation, so fewer repetitions might be required in order to detect a true change. Although fewer repetitions might be performed within a clinical

setting these repetitions have not been interspersed, and the protocols used vary considerably. Within a research or training setting a smaller magnitude of difference occurs between tests so detecting true changes in a measure is more difficult. Performing more repetitions in these settings might be beneficial for detecting true changes. Future research should perform a large number of repetitions over time so a guideline can be established for the number of repetitions to be used during isokinetic strength testing.

Another factor that could have affected the SEM of peak torque and angle of peak torque within the reliability studies was the warm up given prior to the test of maximal contractions. All but two of the reviewed studies performed a warm up as part of their protocol (Madsen, 1996; Kilfoil & St Pierre). The intensity and volume of these warm up periods varied significantly between studies with some warm up periods consisting of either cycling for 5 min or submaximal and maximal isokinetic contractions at different velocities (Ayala et al., 2012; Bernard et al., 2012; Almosnino et al, 2011; Impellizzeri et al., 2008). The types of contractions performed and the period between the warm up and the actual isokinetic test was also variable between studies (Sole et al. 2007; Phillips et al., 2000; Brown et al., 1993). These warm up periods and the time between warm up and testing affect the movement history of the musculotendinous unit. This in turn affects the level of peak torque and angle of peak torque attained during maximal contractions. As the warm up period affects the magnitude of peak torque and angle of peak torque the SEM of these measures is also most likely to change.

Successive reciprocal movements of concentric knee extension and flexion were performed in 13 out of the 17 reviewed reliability studies in table 2 (Ayala et al., 2012; Bernard et al., 2012; Almosnino et al., 2012; Impellizzeri et al., 2008; Maffiuletti et al., 2007; Phillips et al., 2000; Capranica et al., 1998; Brown et al., 1993; Frontera, Hughes, Dallal & Evans, 1993; Kilfoil & St Pierre, 1993; Brown et al., 1992; Stratford et al., 1990; Harding et al., 1988). During successive reciprocal movements peak torque may not be maximised as the consecutive

and combined nature of flexion and extension might be more fatiguing compared to interspersed or non reciprocal movements. Therefore the highest level of peak torque may not have actually been obtained within some of the reliability studies. As these reciprocal movements may have more fatigue associated with them, peak torque or angle of peak torque in these movements could be more variable compared to interspersed or non reciprocal repetitions. This may further affect the ability of these studies to measure true peak torque and could increase the SEM of angle of peak torque.

Some studies used different contraction types compared to the majority of the studies reviewed which used just concentric contractions. For example the studies by Almosnino et al. (2012), Sole et al. (2007) and Wilhite et al. (1992) used concentric and eccentric knee extension as a reciprocal movement. Other studies such as those by Impellizzeri et al. (2008) and Ayala et al. (2012) consisted of eccentric contractions after the concentric sets. Phillips et al. (2000) performed a 4-s isometric test which may have fatigued the quadricep muscle prior to the isokinetic test. In addition to this Maffiuletti et al. (2007) performed an isometric, eccentric and a fatigue protocol after the concentric knee extension task. The different types of contractions before or concurrent with isokinetic concentric knee extension could have affected the magnitude of peak torque attained and consequently it's SEM. Other aspects that were inconsistent between the reviewed studies include the age, number and type of participants recruited, the dynamometers used, the number of test-retest trials and the time between them. These different protocols add to the inconsistency and the variability of results achieved between studies.

A few studies had methodological flaws within their testing protocols which also caused poor reliability of peak torque and angle of peak torque. Bemben and Johnson (1993) had inconsistent results which could be due to half the participants being retested the next day, and the retest session possibly not accounting for muscle soreness. The tested angular velocities

within this study were also randomised for each participant, so variable torque values could have been attained for the velocities of 60°/s and 450°/s in each randomised group. Similarly to Bemben and Johnson (1993), Wilhite et al. (1992) also used different velocity orders which may have affected the reliability of angle of peak torque. Participants in the study by Capranica et al. (1998) performed repetitions as either increasing or decreasing velocities which could have affected the magnitude of peak torque attained for each group and therefore the reliability of this measure.

Not only did some studies have methodological flaws within their testing protocols other studies had incomplete or missing aspects within their reported methods. Frontera et al. (1993) measured angle of peak torque but they did not report any data on it. Additionally they did not report any rest period between the velocities tested or what type of contraction was performed for knee extension. Also when testing the angular velocity of 240°/s participants had to complete 25 consecutive repetitions, which did not account for muscular fatigue. Within the study conducted by Capranica et al. (1998) 22%, 31% and 61% of the participants failed to complete five maximal contractions at 180°/s, 120°/s and 90°/s respectively. This would have caused an incomplete and variable data set of peak torque, further weakening its reliability. Incomplete methods were also reported by Kilfoil and St Pierre (1993) as they failed to state what type of contraction was performed for knee extension. The lack of reported detail in these studies further adds to the inconsistency of methods and results between reliability studies of isokinetic concentric knee extension.

The reviewed studies selected different peak torque and angle of peak torque data for statistical analysis. Some studies selected the highest peak torque as well as averaging the peak torque from the repetitions completed (Maffiuletti et al., 2007; Capranica et al., 1998; Sole et al., 2007). Other studies just averaged peak torque from all the repetitions completed (Ayala et al., 2012; Bernard et al., 2012; Phillips et al., 2000; Wilhite et al., 1992; Harding et al., 1988).

A large proportion of the studies did not actually state whether they selected the highest peak torque or average peak torque for analysis (Almosnino et al., 2012; Bemben & Johnson, 1993; Brown et al., 1993; Kilfoil & St Pierre, 1993; Brown et al., 1992). As some studies averaged peak torque from the completed repetitions this would have reduced the variability within the data set, therefore artificially improving the reliability of peak torque. This was evident in the results by Bernard et al. (2012) as this study used different ICC measures consisting of single and mean trials to calculate the between session reliability of angle of peak torque. The more rigorous ICC measures of single trials showed that angle of peak torque at 60°/s was not reliable, conversely the ICC measures of mean trials found that it was reliable at 60°/s. This shows that the form of reliability measure used to analyse angle of peak torque affects its level of reliability.

Alongside this issue Brown et al. (1993) did not analyse the first and fifth repetitions completed, and the first repetition was discarded by Wilhite et al. (1992). These studies ignore the fact that maximum peak torque could be achieved on the first or fifth repetition. Brown et al. (1992) only recorded data that did not exceed a CV of 9% with any data above this threshold discarded. Additional trials were performed in the studies by Ayala et al. (2012), Phillips et al. (2000) and Brown et al. (1993). The discarded and additional repetitions do not provide the true scores of peak torque and angle of peak torque and impairs the actual reliability of these measures.

The most common forms of reliability measures used within the reviewed studies are ICCs, followed by SEM, CV and Pearson correlation coefficients. Each of these forms of reliability measures were calculated in different ways which may also account for differences in the reliability of peak torque and angle of peak torque between studies. Very few studies analysed the CV and SEM of peak torque and angle of peak torque. Future reliability studies should use CV and SEM as they provide an indication of the within-subject variation of a

measure. These studies should quantify the within-session reliability of peak torque and angle of peak torque as most of the research has focused on between-session reliability of these measures.

It has been suggested that the stabilisation and positioning of the body during isokinetic testing are critical to the reliability of measures such as peak torque and angle of peak torque (Kannus, 1994). In particular, the stabilisation and positioning of the knee axis in relation to the dynamometer axis is integral for measuring angle of peak torque as knee joint angle is based on the angle of the dynamometer lever arm. Most of the reviewed studies do not provide adequate stabilisation of the body during isokinetic testing and this might be one possible cause of error when measuring angle of peak torque. Future studies should provide more stabilisation of the body and knee during isokinetic testing in an attempt to account for this source of error.

Previous isokinetic reliability studies (Ayala et al., 2012; Maffiuletti et al., 2007; Phillips et al., 2000; Brown et al., 1993; Kilfoil et al ., 1993; Brown et al., 1992; Wilhite et al. 1992; Harding et al. 1998) have not outlined the menstrual cycle phase that female participants are in. Thus these studies have not considered the effect of possible changes in hormones during the menstrual cycle upon the consistency and reliability of angle of peak torque. Although it has been shown that fluctuations in hormones during the menstrual cycle may not affect peak torque in sedentary individuals (Gur, Akova & Kucukoglu, 1999), their effect upon angle of peak torque has not yet been established. As the reliability of angle of peak torque is equivocal fluctuations in hormones may have an effect on the consistency of this measure and ultimately its SEM, future research needs to investigate such an effect. Due to this future studies investigating the reliability of isokinetic angle of peak torque should use male participants to account for the changes in hormones from the menstrual cycle.

2.19 Section summary

Angle of peak torque is thought to be a significant measure as it may indicate possible risk of muscular injury. Specifically, it is hypothesised if angle of peak torque occurs towards the end range of a concentric movement, the risk for muscular soreness and strains is greater. This theory is speculative and hypothetical as it is firstly based on relating the length-tension relationship of a single muscle fiber to the torque-angle relationship of a single joint. Secondly this theory is speculative as angle of peak torque is claimed to be reliably measured by Brockett et al. (1999) but there is no rigorous scientific investigation that supports such a claim. Research investigating angle of peak torque within training studies assumes that it is a reliable phenomenon without any hard scientific evidence. Determining the reliability of angle of peak torque will verify whether further research should be performed in this area and the true significance of angle of peak torque.

Most of the reliability studies reviewed showed that peak torque was reliable and angle of peak torque was unreliable based on the methods employed in testing and analysis. As angle of peak torque was shown to be unreliable this provides a good reason for further investigation of the within-subject variation of this measure. Although peak torque was shown to be reliably measured within the majority of the studies reviewed, the design of these studies was not rigorous with some protocols inadequately described. The primary goal of an isokinetic test is to reduce the within-subject variation of a measure as much as possible so the true measurement score can be revealed. This allows for small changes in a measure to be tracked over time and better interpretation of the measure. Within-subject variation is not often considered within isokinetic strength testing as ICCs have primarily been used. Additionally, low levels of within-subject variation are not often achieved within testing despite the reliance and popularity of isokinetic dynamometry in research, clinical and exercise training settings.

The other goal of an isokinetic test is to maximise force production. These two key goals were not considered by most of the reviewed reliability studies as some of the test protocols consisted of: two to six grouped repetitions, different warm up volumes and intensities, successive reciprocal movements of knee flexion and extension, limited rest between the velocities tested, different types of reciprocal contractions and a large age range of participants. These factors varied significantly between studies and a rationale was not typically provided for them. Such factors could have added to the observed biological variability of peak torque and angle of peak torque, therefore possibly increasing the within-subject variation of these measures. Additionally, those studies that averaged repetitions for data analysis would have provided a false indication of the reliability of peak torque and angle of peak torque.

Other inconsistencies between studies include the type of dynamometers used, the number and type of participants, the number and period of retest trials, the number of repetitions selected for analysis and the removal of repetitions from analysis. Although the limitations of the reviewed studies may have affected the consistency of peak torque and angle of peak torque, angle of peak torque may always be relatively inconsistent due to its biological nature and the total amount of error associated with it.

Nonetheless due to the limitations of the reviewed studies the true magnitude of within-subject variation of peak torque and angle of peak torque is unknown. Future research should account for these limitations and factors that cause force variability in order to reduce the within-subject variation of peak torque and angle of peak torque. Specifically, this research should investigate the consistency of peak torque and angle of peak torque with multiple grouped and interspersed repetitions. No published research such as this has been conducted previously. It is important to conduct this research as it might be possible to reliably measure angle of peak torque of the knee extensors. Determining the within-subject variation of angle of peak torque may help establish whether this measure is clinically useful, in particular

whether true changes or the effects of an intervention can be detected when measuring it. Future research of multiple and interspersed repetitions will also help establish a universal testing protocol and possibly provide guidelines for the reliability of peak torque and its angle. Finally such research will provide an understanding of the effects of the movement history of grouped and interspersed repetitions on peak torque and angle of peak torque.

Table 2. Summary of isokinetic reliability studies of peak torque and angle of peak torque during concentric knee extension

KEY: KE = Knee extension; KF = Knee flexion; PT = Peak torque; ROM = range of motion; CV = Coefficient of variation; LOA= Limits of agreement; ICC = Intraclass correlation coefficient; SEM = Standard Error of Measurement;% Diff = Percent difference in mean scores; MDC = Minimal Detectable Change

Author	Methods	Reliability of peak torque and angle of peak torque for concentric knee extension	Conclusions
Ayala et al. 2012	Participants: •26 male and 24 female; performed 3-5 h moderate exercise each week Dynamometer, setup and familiarisation: •Biodex 3; 90˚ ROM; Prone position; sampling frequency – not stated •Familiarisation – 1 week before test – several submax and maximal reps Warm up: •5 min cycle; 4 x sub maximal and 2 x maximal repetitions of concentric and eccentric KE and KF •3 min break between warm up and testing Test protocol: •Tested dominant leg at 60˚/s, 180˚/s and 240˚/s •2 x reciprocal concentric KE and KF contractions first each velocity; then eccentric KE and KF contractions at each velocity •30-s rest between repetitions; 5 min between concentric and eccentric phases •Three testing sessions; 72 – 96 h between sessions	**Between-session reliability** PEAK TORQUE: CV / ICC (3,1): — ANGLE OF PEAK TORQUE: CV / ICC (3,1): 60˚/s: 16% / 0.71 — 12% / 0.22 180˚/s: 15% / 0.78 — 19% / 0.32 240˚/s: 14% / 0.87 — 9% / 0.32 •CV of peak torque across all velocities was poor. •ICC of peak torque for 60˚/s and 180˚/s was poor; 240˚/s was good. •CV of angle of peak torque at 60˚/s and 240˚/s was poor; 180˚/s very poor •ICC of angle of peak torque was poor at all velocities. Data analysis: •Averaged two trials for each velocity for analysis •If variation of >5% was found in PT values between cycles an extra cycle was performed. Two most related cycles were used	Between-session reliability of peak torque at all velocities was poor including 240˚/s. Between-session reliability of angle of peak torque across all velocities was poor.
Bernard et al. 2012	Participants: •29 male athletes (age 18-30 y):15 soccer; 7 Gymnasts; 7 Swimmers •Involved in sport minimum 3 y; train x 2 per week •Soccer and gymnast athletes – elite Dynamometer, setup and familiarisation: • Cybex Orthotron KT; 90˚ ROM; Seated position; sampling frequency – not stated; • No familiarisation session Warm up: •10 min cycle; 5 min hamstring/quadricep stretching; 4 submaximal repetitions of concentric KE and KF before each velocity Test protocol: •Tested dominant and non dominant limb •4 x reciprocal concentric KF and KE at 60˚/s first then same for 180˚/s •3 min rest between each limb tested; 5 min rest between the two velocity phases • 3 testing sessions in same day – 45 min between each session	**Between-session reliability of angle of peak torque** SEM% / CV / ICC (1,1) / ICC (1,k) Dom 60˚/s: 5% / 5% / 0.61 / 0.82 Dom 180˚/s: 8% / 7% / 0.46 / 0.72 Ndom 60˚/s: 4% / 3% / 0.60 / 0.82 Ndom 180˚/s: 7% / 6% / 0.48 / 0.74 ICC (2,1) / ICC (2,k) / ICC (3,1) / ICC (3,k) Dom 60˚/s: 0.62 / 0.83 / 0.71 / 0.88 Dom 180˚/s: 0.47 / 0.73 / 0.51 / 0.75 Ndom 60˚/s: 0.61 / 0.83 / 0.67 / 0.86 Ndom 180˚/s: 0.50 / 0.75 / 0.55 / 0.55 • SEM% = % of mean value; mean value of two sessions Data analysis: • ICC number 1 =. Single scores; letter k = Averaged score	SEM and CV for angle of peak torque at 60˚/s was good, 180˚/s poor. All ICCs for angle of peak torque at 180˚/s was poor. The ICC single score (1) of APT at 60˚/s was poor, averaged (k) ICC of APT at 60˚/s was good. APT at 60˚/s had good reliability, APT at 180˚/s was not reliable.

Author	Methods	Reliability of peak torque and angle of peak torque for concentric knee extension	Conclusions
Almosnino et al. 2011	Participants: •25 males (mean age 22.8 ± 3.5y) and 20 females (mean age 22.4 ± 2.3y) •Performed 5 ± 2 h weekly physical activities or sports Dynamometer, setup and familiarisation: •Biodex system 3; seated position; 60˚ ROM; sampling frequency 100Hz •Familiarisation – same day testing – 15 reciprocal concentric KE/KF reps at 60˚/s; 5 concentric-eccentric reps each velocity Warm up: •15 x concentric KE and KF reps at 60˚/s – low effort level •5 x KE and KF concentric-eccentric repetitions at 30˚/s and 120˚/s •2 – 3 maximal concentric/eccentric KE and KF repetitions at each testing velocity • 3 min rest between warm up and test Test protocol: •Angular velocities 30˚/s and 120˚/s - not state what limb was tested •3 x concentric and eccentric reps of KE – at each velocity; same KF •5-s pause between concentric and eccentric repetitions •5 min rest between sets of KE and sets KF •Rest period of 2-3 min between velocities •Two testing sessions – 10 ± 5 d	**Between-session reliability – Peak torque** Males % Diff CV LOA (±) ICC (2,1) 30˚/s 1% 5% 14% 0.92 120˚/s 1% 5% 13% 0.95 Females % Diff CV LOA (±) ICC (2,1) 30˚/s 2% 4% 13% 0.86 120˚/s 2% 4% 13% 0.86 DID NOT MEASURE ANGLE OF PEAK TORQUE Data analysis: •Did not state whether the mean of each repetition or the highest peak torque or angle of peak torque repetition was used for statistical analysis.	Peak torque had very good between-session reliability
Impellizzeri et al. 2008	Participants: •18 physically active participants; age range 21 – 28 y Dynamometer, setup and familiarisation: •Cybex NORM; ROM 80˚; Seated position; sampling frequency – not stated •No familiarisation session Warm up: •20 submaximal reciprocal concentric KE and KF; followed by 20 submaximal reciprocal eccentric KE and KF •5 - 6 submaximal practice repetitions before concentric and eccentric tests Test protocol: •Both legs tested •3 x reciprocal concentric KE and KF at velocities 60˚/s, 120˚/s and 180˚/s •3 x eccentric KE 60˚/s – non reciprocal single movement •3 x eccentric KF 60˚/s – non reciprocal single movement •1 min rest between all sets •Three testing sessions – 96 h between sessions	**Between-session reliability – Peak torque** Right leg SEM LOA (±) ICC (2,1) MDC% 60˚/s 4% 12% 0.98 12% 120˚/s 5% 13% 0.97 16% 180˚/s 4% 11% 0.98 15% Left leg SEM LOA (±) ICC (2,1) MDC% 60˚/s 5% 13% 0.95 17% 120˚/s 5% 15% 0.97 16% 180˚/s 5% 13% 0.98 18% DID NOT MEASURE ANGLE OF PEAK TORQUE Data analysis: • Highest peak torque selected for analysis	Peak torque had very good between-session reliability

Author	Methods	Reliability of peak torque and angle of peak torque for concentric knee extension	Conclusions
Maffiuletti et al. 2007	Participants: •15 male and 15 female; age 23 - 42 y; active athletes Dynamometer, setup and familiarisation: •Con-trex; 70˚ ROM; Seated position; sampling frequency – 100Hz •No familiarisation session Warm up: •20 submax concentric and eccentric KE and KF reps @ 15˚/s; 2-3 submax repetitions before each velocity Test protocol: •Tested dominant leg only •3 x concentric reciprocal KE and KF contractions at 60˚/s, 120˚/s 180˚/s •Followed by isometric, eccentric and fatigue test •1 min passive rest between each velocity •Two testing sessions; 7 d between sessions	**Within-session reliability** PEAK TORQUE: CV / ICC (2,1); ANGLE OF PEAK TORQUE: CV / ICC (2,1) 60˚/s: 3% / 0.99; 4% / 0.93 120˚/s: 2% / 0.99; 4% / 0.97 180˚/s: 2% / 0.99; 4% / 0.94 **Between-session reliability** PEAK TORQUE: CV / ICC (2,1); ANGLE OF PEAK TORQUE: CV / ICC (2,1) 60˚/s: 3% / 0.98; 3% / 0.91 120˚/s: 3% / 0.99; 3% / 0.92 180˚/s: 3% / 0.99; 3% / 0.91 Data analysis: •Only two trials giving the highest peak torques were used •Within session reliability trial 1 compared to trial 2 •Between session (average trial 1 and 2 compared to session 2)	Very high within and between-session reliability of peak torque and angle of peak torque across all velocities.
Sole et al. 2007	Participants: •11 men (mean age 20 ± 1y) and 7 women (mean age 22 ± 3y) Dynamometer, setup and familiarisation: •Kin-Com 500H; Seated position; ROM 85˚; sampling frequency – not stated • No familiarisation session Warm up: •10 submaximal and 2 maximal contractions; 1 min break between warm up and testing – before KE and KF test Test protocol: •Tested dominant leg only •3 x concentric and eccentric maximal KE at 60˚/s – each concentric contraction followed by eccentric contraction – 15-s rest between all contractions •3 x concentric and eccentric maximal KF at 60˚/s – each concentric contraction followed by eccentric contraction – 15-s rest between all contractions •Two testing sessions – 7 d apart	**Between-session reliability – Peak torque** Highest / Mean ICC(3,1): 0.93 / 0.95 SEM (N.m): 8 / 6 SEM%: 6 / 5 MDC (N.m): 23 / 18 MDC %: 18 / 15 DID NOT MEASURE ANGLE OF PEAK TORQUE Data analysis: •Mean and highest of peak torque was used for statistical analysis	Peak torque had very good between-session reliability

Author	Methods	Reliability of peak torque and angle of peak torque for concentric knee extension	Conclusions
Phillips et al. 2000	Participants: •8 male and 12 female (range 23 – 39 y);Non resistance trained •12 participants experienced soft tissue discomfort during tested and torque value for muscle group was not used Dynamometer, setup and familiarisation: •Kin-Com; 90˚ ROM; Seated position; sampling frequency – not stated • No familiarisation session Warm up: •2 submaximal trials for each velocity Test protocol: •60˚/s and 120˚/s; 3 x reps at each angular velocity •Tested dominant (Dom) and non dominant (Ndom) legs; randomised for participants •Isometric test performed before isokinetic •Isometric test: 3 – 4-s, KE then KF •Isokinetic test – concentric KE and KF •3-s pause between KE and KF phases •2 min rest between each velocity •Two testing sessions – 2 wks apart	**Within-session reliability – ICC (3,1):** PEAK TORQUE ANGLE OF PEAK TORQUE Dom 60˚/s: 0.99 0.41 Dom 120˚/s: 0.99 0.88 Ndom 60˚/s: 0.99 0.83 Ndom 120˚/s: 0.99 0.83 **Between-session reliability – ICC (1,1):** PEAK TORQUE ANGLE OF PEAK TORQUE Dom 60˚/s: 0.98 0.10 Dom 120˚/s: 0.95 0.57 Ndom 60˚/s: 0.97 0.51 Ndom 120˚/s: 0.98 0.28 Data analysis: • Three trials were averaged for analysis • Additional trials performed if torque curves were not aligned closely to each other	Peak torque at all velocities had a very good within and between-session reliability. Angle of peak torque at 60˚/s had very poor within-session reliability, whereas 120˚/s was good. Between-session reliability for angle of peak torque was very poor.
Capranica et al. 1998	Participants •18 elderly women, mean age 68 ± 5 y; range 60 – 78 y •All subjects completed at least three successful contractions. Dynamometer, setup and familiarisation: •Merac; 80˚ ROM; Seated position; sampling frequency – not stated •No familiarisation session Warm up: •5 min cycle; accustomed to each velocity Test protocol: •Tested dominant and non dominant limbs; dominant limb first •Angular velocities 90˚/s, 120˚/s and 180˚/s •5 x reciprocal concentric KE and KF at each velocity •Two testing sessions – 15 d apart Data analysis: •Highest and average of best three values at each velocity used to test differences in each test session	**Within-session reliability ICC: Best three performances** PEAK TORQUE 90˚/s: 0.03 120˚/s: 0.23 180˚/s: 0.21 **Between-session reliability ICC: Best and mean values of peak torque** Best PT Mean PT 90˚/s: 0.70 0.66 120˚/s: 0.80 0.29 180˚/s: 0.73 0.74 •ARTICLE NOTES THAT IT MEASURED ANGLE OF PEAK TORQUE BUT IT DID NOT REPORT IT	Both within and between-session reliability of peak torque was poor.

Author	Methods	Reliability of peak torque and angle of peak torque for concentric knee extension	Conclusions
Madsen 1996	Participants: •24 healthy non athletic females; 18 – 52 y; 53 – 98 kg •No prior experience of muscle strength tests Dynamometer, setup and familiarisation: •Cybex 6000; 90˚ ROM; Seated position; sampling frequency – not stated •No familiarisation session Warm up: •Only in test session 3. Single leg stationary cycle @ 50W for 5 min •1 x submaximal trial Test protocol: •Velocities 30˚/s, 120˚/s, 240˚/s and isometric. Velocity 30˚/s was repeated for test 1. •4 separate testing days. Median of: 2 d between test 1 and 2, 7 d between test 1 and 3 and 32 days between test 1 and 4. •Concentric KE of both limbs, Elbow Flex and Ext Dominant arm •3 x repetitions at each angular velocity, 10-s rest between repetitions •60-s rest between each angular velocity	**Within-session reliability - Test session 1** CV of Peak torque 30˚/s: 8% 240˚/s: 3% **Between-session reliability – Between tests 1 and 2** CV of Peak torque 30˚/s: 8% 240˚/s: 5% **Between-session reliability – Between tests 1 and 4** CV of Peak torque 30˚/s: 7% 240˚/s: 8% • Selected two highest values of peak torque for analysis	Peak torque had good within-session reliability at 240˚/s and between-session reliability for tests 1 and 2 at 240˚/s. But had poor within-session reliability at 30˚/s as well as poor reliability between sessions 1 and 2 at 30˚/s. Poor between-session reliability of peak torque was also evident between tests 1 and 4 at 30˚/s and 240˚/s.
Bemben and Johnson 1993	Participants: •30 male students; mean age 17.6 – 22.6 y •20 NCAA athletes (10 soccer,10 baseball);10 non athlete controls Dynamometer, setup and familiarisation: •Biodex B-2000; 90˚ ROM; Seated position; ; sampling frequency – not stated •No familiarisation session Warm up: •3 min stationary bike Test protocol: •Tested dominant and non dominant legs •Angular velocities 60˚/s and 450˚/s •Concentric KE at both velocities; 3 x repetitions at each angular velocity – testing order randomised •30-s rest between each repetition; 3 min rest between tests of each leg •Random sample of 15 subjects retested; 5 participants in each group •Two testing session; second session next day	**Between-session reliability** Pearson correlation coefficients: RL = Right leg LL = Left leg PEAK TORQUE ANGLE OF PEAK TORQUE 60˚/s RL LL RL LL Control: 0.18 0.42 0.64 0.64 Baseball: 0.49 0.79 0.17 0.90 Soccer: 0.79 0.91 0.86 0.77 450˚/s RL LL RL LL Control: 0.47 0.05 0.81 0.78 Baseball: 0.82 0.78 0.34 0.15 Soccer: 0.69 0.78 0.97 0.46 Data analysis: •Did not state whether the mean of each repetition or the highest peak torque or angle of peak torque was used for statistical analysis.	Mixed findings for both peak torque and angle of peak torque for all groups. No speed showed higher reliability of peak torque. Overall peak torque and angle of peak torque had poor reliability.

Author	Methods	Reliability of peak torque and angle of peak torque for concentric knee extension	Conclusions
Brown et al. 1993	Participants: •14 males and 6 females; Mean age 28.8 y Dynamometer, setup and familiarisation: •Biodex II; 80˚ ROM; Seated position; sampling frequency – not stated •No familiarisation session Warm up: •5 min cycle; reciprocal concentric KE and KF 3 x submax and 2 x maximal reps at 450˚/s, 180˚/s and 60˚/s Test protocol: •Tested only one leg •5 x reciprocal concentric KE and KF at 60˚/s, 120˚/s, 180˚/s, 240˚/s, 360˚/s and 450˚/s •1 min rest between velocities •Two testing sessions – 1 d apart	**Between-session reliability** Pearson correlation coefficient and (ICC 2,1): PEAK TORQUE ANGLE OF PEAK TORQUE 60˚/s: 0.98 (0.98) 0.61 (0.57) 120˚/s: 0.96 (0.96) 0.44 (0.41) 180˚/s: 0.96 (0.95) 0.57 (0.54) 240˚/s: 0.92 (0.92) 0.27 (0.23) 360˚/s: 0.95 (0.93) 0.68 (0.69) 450˚/s: 0.95 (0.93) 0.66 (0.63) Data analysis: •First and last repetitions discarded – only 3 reps used for analysis •Did not state whether the mean of each repetition or the highest peak torque or angle of peak torque repetition was used for statistical analysis.	Peak torque had very good between-session reliability across all velocities, whereas angle of peak torque was very poor.
Frontera et al. 1993	Participants •71 males (mean age 60.2 y) and 107 females (mean age 60 y) Dynamometer, setup and familiarisation: •Cybex II; Seated position; sampling frequency – not stated •No familiarisation session Warm up •3 – 4 maximal repetitions Test protocol • Reciprocal KE and KF contractions; then elbow flexion and extension •Angular velocities 60˚/s and 240˚/s for knee •5 x MVCs at 60˚/s and 25 x MVCs at 240˚/s •Two testing sessions – 7 to 10 d apart •Do not state whether participants performed concentric contraction	**Between-session reliability** Pearson correlation co-efficient: Peak torque: Males: Females: 60˚/s: 0.75 0.74 •The study measured angle of peak torque. BUT DID NOT REPORT ANY DATA ON ANGLE OF PEAK TORQUE. Data analysis: •Did not state whether the mean of each repetition or the highest peak torque or angle of peak torque repetition was used for statistical analysis.	Between-session reliability of peak torque was poor.

Author	Methods	Reliability of peak torque and angle of peak torque for concentric knee extension	Conclusions
Kilfoil et al. 1993	Participants •4 male (mean age 47.5 ± 10 y) and 4 female (mean age 56.8 ± 16 y) •All participants had post-poliomyelitis •Only 5 subjects had sufficient lower limb strength for bilateral contractions Dynamometer, setup and familiarisation: •Cybex II; Seated position; sampling frequency – not stated •No familiarisation session Warm up • No warm up reported Test protocol •Reciprocal KE and KF contractions x 3 reps •Angular velocities 60˚/s, 120˚/s, 180˚/s and 240˚/s •2 min rest between velocities •Bilateral contractions where possible •Three testing sessions – 1 wk apart •Did not state whether participants performed concentric contraction Data analysis: •Did not state whether the mean of each repetition or the highest peak torque or angle of peak torque repetition was used for statistical analysis.	**Between-session reliability** ICC across three test sessions – both limbs: PEAK TORQUE / ANGLE OF PEAK TORQUE 60˚/s: 0.82 – 0.95 / 0.88 – 0.90 120˚/s: 0.95 – 0.99 / 0.56 – 0.88 180˚/s: 0.87 – 0.98 / 0.54 – 0.84 240˚/s: 0.98 – 0.99 / 0.34 – 0.72 ICC over two test sessions – both limbs: PT day 1 - 2: / PT day 2 - 3: 60˚/s: 0.91 – 0.98 / 0.93 – 0.98 120˚/s: 0.92 – 0.98 / 0.97 180˚/s: 0.86 – 0.98 / 0.82 – 0.97 240˚/s: 0.98 / 0.96 – 0.98	Between-session reliability of peak torque was very good. Between-session reliability of angle of peak torque was poor across all velocities except at 60˚/s.
Brown et al. 1992	Participants: •8 male and 12 female; 15 – 56 y Dynamometer, setup and familiarisation: •LIDO Active; 70˚ ROM; Seated position; sampling frequency – not stated •No familiarisation session Warm up: •5 min cycle; 3 - 5 submax reps KE and KF and 1-3 max reps at each velocity Test protocol: •Tested right leg only •Reciprocal concentric KE and KF at 60˚/s, 180˚/s, 300˚/s and 400˚/s •5 repetitions performed at each angular velocity •90-s between each angular velocity •Two testing sessions - 2 d between sessions	**Between-session reliability** Pearson correlation coefficient: PEAK TORQUE / ANGLE OF PEAK TORQUE 60˚/s: 0.96 / 0.49 180˚/s: 0.98 / 0.92 300˚/s: 0.98 / 0.86 400˚/s: 0.99 / 0.77 Data analysis: •Did not state whether the mean of each repetition or the highest peak torque or angle of peak torque repetition was used for statistical analysis.	Very good between-session reliability of peak torque across all velocities Angle of peak torque was only reliable at 180˚/s and 300˚/s.

Author	Methods	Reliability of peak torque and angle of peak torque for concentric knee extension	Conclusions
Wilhite et al. 1992	Participants •14 females, 4 males; 22 – 37 y; not engaged in strength training Dynamometer, setup and familiarisation: •Kin-Com; 85˚ ROM; Seated position; sampling frequency – not stated •No familiarisation session Warm up •Modified hurdler stretch 30-s x 3 reps; 2 submax reps, 1 maximal concentric and eccentric KE contraction •1 min between warm up and test Test protocol •Right leg tested •Concentric contractions of KE performed first; prior to eccentric contractions •5-s pause between each contraction •60˚/s, 120˚/s and 180˚/s; 4 x repetitions at each angular velocity •1 min between each tested velocity •Three testing sessions – 3 wks •Do not state speed during knee flexion phase	**Within-session reliability ICC 1,1:** PEAK TORQUE ANGLE OF PEAK TORQUE 60˚/s: 0.80 – 0.99 0.06 – 0.91 120˚/s: 0.90 – 0.99 -0.18 – 0.92 180˚/s: 0.88 – 0.99 -0.14 – 0.72 **Between-session reliability ICC 1,1:** PEAK TORQUE ANGLE OF PEAK TORQUE 60˚/s: 0.76 0.64 120˚/s: 0.85 0.63 180˚/s: 0.80 0.40 Data analysis: •First repetition was not analysed •Within-session ICCs were based on the mean of the 4 repetitions from each testing session.	Within-session reliability of peak torque was very good across all velocities but angle of peak torque was mostly very poor. Between-session reliability of peak torque was poor at 60˚/s and good at 120˚/s and 180˚/s. Whereas angle of peak torque was poor across all velocities.
Stratford et al. 1990	Participants •12 females and 4 males; age 23.6 ± 2.3 y; 64.6 ± 8.3 kg Dynamometer, setup and familiarisation: •Cybex II; Seated position; Knee ROM and sampling frequency not stated •No familiarisation session Warm up •5 min cycle; 3 x submaximal trials and 1 x maximal trial •2 min rest prior to testing Test protocol •Right leg tested •1 x angular velocity at 60˚/s •5 x concentric reciprocal KE and KF repetitions •Each participant performed a no rest and rest protocol – randomised order •Two randomised groups 1. no rest and rest, 2. Rest and no rest •No rest protocol = 5 grouped repetitions of KE and KF •Rest protocol = 30-s rest between each KE and KF repetition •1-s pause between KE and KF contractions	**Within-session reliability** No rest protocol Rest protocol Highest PT Mean PT Highest PT Mean PT ICC 0.93 0.98 0.98 0.99 SEM 12 N.m 5 N.m 7 N.m 3 N.m • Two types of data was selected: - Highest peak torque (PT) over 5 repetitions - Mean peak torque (PT) over 5 repetitions ICC (2,1) used for Highest PT, ICC (2,5) used for Mean PT	Peak torque was reliable within a session for both the rest protocol and no rest protocol. The rest protocol had a lower within-session reliability compared to the no rest protocol.

Author	Methods	Reliability of peak torque and angle of peak torque for concentric knee extension	Conclusions
Harding et al. 1988	Participants: •14 healthy females 21.6 ± 1.6 y • No prior experience of isokinetic testing Dynamometer, setup and familiarisation: •Kin-Com; 90˚ ROM; Seated position; sampling frequency – not stated •No familiarisation session Warm up: •4 submaximal of KE and KF repetitions; 2 min rest before testing Test protocol: •Only right leg tested •6 x reciprocal concentric KE and KF contractions at 60˚/s •5-s pause between extension and flexion movement •30-s rest between KE and KF repetitions •Two testing sessions – 8 d between sessions Data analysis: •Averaged 6 repetitions of peak torque and angle of peak torque for ICC and SEM	**Within-session reliability** PEAK TORQUE ANGLE OF PEAK TORQUE ICC 60˚/s: 0.99 0.93 **Between-session reliability** PEAK TORQUE ANGLE OF PEAK TORQUE ICC 60˚/s: 0.96 0.63 PEAK TORQUE ANGLE OF PEAK TORQUE Overall ICC: 0.95 0.63 SEM: 5 N.m 3˚ 95% CI: 11 N.m 6˚	Very good within and between-session reliability of peak torque Good within and between-session reliability of angle of peak torque Overall reliability of peak torque and angle of peak torque was good.

Chapter 3 - Methods

3.1 Participants

Twenty four physically active or trained male participants were recruited from the School of Physical Education at the University of Otago for the current study. Physically active or trained individuals were the selected sample for this study as these type of participants were used in the majority of the previous isokinetic research. Physically active or trained participants were those individuals who performed regular exercise or strenuous activities for at least 2 hr per week and did this consistently over the past 6 months. Participants were excluded from the study if they had medical conditions contraindicating muscular effort and a history of lower limb musculoskeletal problems or injuries.

A full explanation of the study requirements was provided to the participants and they were asked to provide informed consent and complete a screening questionnaire. Participants were instructed not to perform any vigorous or intense exercise within 24 hr of the testing sessions. Participants were also asked to keep their pre-testing physical activity, sleep patterns and diet consistent between testing sessions. The participants' intake of caffeine or supplements were not controlled within the study. Participants' physical activity levels were monitored between sessions, and their minutes of resistance training and total minutes of training performed on average each week were recorded. This average was based on the participants' weekly training over the previous six months. Category A ethical approval (10/137) was confirmed by the University of Otago human ethics committee for this research project.

3.2 Isokinetic testing

3.2.1 Familiarisation and testing sessions

Testing employed the Biodex System II isokinetic dynamometer (Biodex Corporation, Shirley, NY) (See Appendix B). A familiarisation session was conducted one day prior to the first testing session. Initially this consisted of obtaining the participant's height and body

mass. Within this session participants performed five submaximal concentric knee extension repetitions at 60°/s. These repetitions were at approximately 60 – 70% of the participants' maximum effort. Participants then performed five consecutive maximal concentric knee extension movements at 60°/s, followed by five maximal repetitions interspersed with a 30-s rest period. Thorough instructions and details of how to perform the knee extension task were given.

During three different testing sessions participants performed 50 maximal concentric knee extension movements with their dominant leg. There was a minimal 48 hr rest period between each testing session with the order of three testing sessions randomised for every participant. One testing session involved ten sets of five grouped knee extension repetitions with a 120-s rest period between each set (Gr-R), and was chosen to represent contemporary isokinetic testing protocols. Another session involved participants performing 50 interspersed knee extension movements with a 30-s rest period between each repetition (IR-30). The other testing session involved 50 interspersed knee extension repetitions with a 60-s rest period between repetitions (IR-60). No warm up was provided to participants prior to all testing sessions. No warm up was performed in order to examine the effect of movement history (i.e. how one repetition after another) affects peak torque and its angle for all repetition protocols. The testing sessions for the individual participants occurred at approximately the same time of the day. The interspersed protocols (IR-30 and IR-60) were chosen to investigate the consistency of peak torque and its angle, and the magnitude changes of peak torque in comparison to the contemporary protocol. Specifically 30 and 60-s rest periods between repetitions were chosen as these rest periods may optimise muscle properties such as PCr repletion, PAP and movement history which may increase peak torque, and possibly result in a lower SEM of peak torque and its angle.

3.2.2 Measures

Measures obtained during testing included dynamometer angle and torque. Data was collected in Chart Pro version 7.0.1 software (ADInstruments, NZ) with a sampling frequency of 1000Hz. A powerlab 8/30 (ADInstruments, NZ) was used to transfer the data from the Biodex isokinetic dynamometer to the Chart software programme. Prior to the commencement of testing, calibration checks of dynamometer angle and torque were taken from the Biodex isokinetic dynamometer and analysed on the Chart software. The Biodex isokinetic dynamometer setup had a soft cushioning, medium sensitivity, and the percentage range dials were set to 100%. Other models of the Biodex isokinetic dynamometer have been shown to be reliable in measuring torque, velocity and angle within and between days (Drouin, Valovich-McLeod, Shultz, Gansneder & Perrin, 2004; Taylor, Sanders, Howick & Stanley, 1991). Dynamometer angle was used to infer measures of true knee joint angle as the knee axis appears to moves consistently from one repetition to another during concentric knee extension, as shown in the preliminary study (See Appendix A). As the knee axis moves appears to move consistently from one repetition to another, there might be a consistent difference between true knee joint angle and dynamometer angle during knee extension. As a consistent difference may exist, dynamometer angle can be used to infer measures of true knee joint angle (See Appendix A).

Prior to each testing session the participant's level of muscle soreness was assessed and recorded on a Visual Analogue Scale (VAS) (See Appendix C). Participants were asked to mark a line on the VAS scale according to their level of perceived muscle soreness in their dominant limb at the time of assessment. A blank scale was used for each testing session to avoid bias from previous measurements. A VAS score was determined by measuring the distance (cm) from the left end of the line (no soreness) to the point marked by the participant. This was measured to the nearest 0.1 cm. The VAS has been shown to be a reliable and valid

measure for determining the intensity of human pain (Price, McGrath, Rafii & Buckingham, 1983). The participants VAS score recorded in the familiarisation session was used as a baseline score for subsequent testing sessions. If the participants VAS score was 2 cm greater than the baseline score testing sessions were delayed until the VAS score was within this 2 cm range. A 2 cm range was used as the cut off for further testing as this represents the error threshold associated with VAS markings (Kelly, 2001), and any score greater than this range would most likely represent muscle soreness.

3.2.3 Isokinetic setup

Limb dominance was established by asking participants which leg they would kick a ball with. Participants were seated in the Biodex chair and secured using a specialised harness system. This system was designed to provide more stabilisation of the body than the recommended setup outlined by the manufacturer (See Appendix D).

The lateral femoral condyle of the dominant leg was identified and marked, with this bony landmark aligned to the axis of the Biodex isokinetic dynamometer. The tested leg was secured firmly with an ankle strap positioned superior to the medial malleolus. Straps also secured the thigh and waist. Shoulder straps were secured diagonally across the torso to the opposite hip. Knee range of motion was set from 100° to 20°. Dynamometer angle was set to anatomical angle of the knee, 90° corresponded to the knee at right angles and 0° corresponded to the knee beyond full extension (See Appendix B). The angular velocity of the Biodex isokinetic dynamometer was set to 60°/s for the knee extension phase and to 300°/s for the knee flexion phase. No verbal encouragement was given to the participant during testing. Visual feedback of torque from each repetition was displayed during testing, with the participant's highest level of torque achieved used as their acquired target for each repetition.

Prior to testing, participants were instructed to do their best and to push as hard as they could during knee extension like they were kicking a ball, and to relax the leg during the knee

flexion phase. A Borg rating of perceived exertion scale from 6 – 20 (6 no exertion at all, 20 maximal exertion) was explained to the participants. Each participant was asked to perform each contraction at level 20 on this scale. Once the participant was strapped into the chair they performed 50 maximal concentric knee extension movements of their dominant limb according to the assigned randomised order of the testing sessions. At the conclusion of each testing session, participants were given a 5 min warm down on a Monark ergomedic 828E stationary bike (2 kp at 75 rpm) and completed a standing quadricep stretch for four sets of 30-s.

3.3 Data acquisition and statistical analysis

Measures of peak torque and angle of peak torque from the Chart software were extracted for each repetition using Matlab R2009a version 7.8.0.347 (The MathWorks, Natick, MA). The distributions and heteroscedasticity of peak torque and angle of peak torque over all 50 repetitions for interspersed and grouped repetitions were checked using the Shapiro-Wilk test. This test demonstrated that peak torque and angle of peak torque data over all 50 repetitions for interspersed and grouped repetitions was normally distributed and that heteroscedasticity was not present.

Means and standard deviations (±) were calculated for peak torque and angle of peak torque. Intraclass Correlation Coefficient ($ICC_{3,1}$) with 95% confidence intervals (95% CI) was also calculated for peak torque and angle of peak torque. This was a two-way single measure consistency ICC. Standard Error of Measurement (SEM) of peak torque and angle of peak torque was calculated using the formula: $SEM = SD \times \sqrt{(1 - ICC)}$ (Sole et al., 2007). The SD used in this calculation is the between-subject SD of each trial analysed. Minimal Detectable Change (MDC) of peak torque and angle of peak torque was calculated using the formula: $1.96 \times \sqrt{2} \times SEM$ (Impellizzeri et al., 2008). SEM and MDC of peak torque and angle of peak torque was expressed as a raw value (N.m or $^{\circ}$) and as a percentage of the group mean

(SEM% or MDC%). The peak torque and angle of peak torque data selected for analysis of within-session reliability is outlined in figure 4.

A one way repeat measures ANOVA was used to calculate significant differences in mean peak torque between grouped and interspersed protocols of50 repetitions. A dependent t-test was used to calculate significant differences in the highest peak torque ofthe first five repetitions and all 50 repetitions. Differences were considered significant if $p < 0.05$. Sample size for the current study was based on the sample size of previous reliability studies conducted by Bernard et al. (2012), Maffiuletti et al. (2007) and Bemben and Johnson (1993). All statistical analyses were performed with SPSS 21.0 statistical software (SPSS Inc., Chicago, IL, USA). All data analysed and displayed in tables and figures of Chapter 4 are for 24 young adult males. Except the data for table 11 where there are 12 participants for each high and low subgroup, and the data displayed in figures 7 and 8 are for individual participants.

Participants' body mass, minutes of resistance training per week and minutes of training per week were analysed individually as covariates through a linear regression model (SPSS) in order to explore their effects on mean peak torque and angle of peak torque for Gr-R, IR-30 and IR-60. The data analysed were peak torque and angle of peak torque of all 50 repetitions of concentric knee extension for all 24 participants.

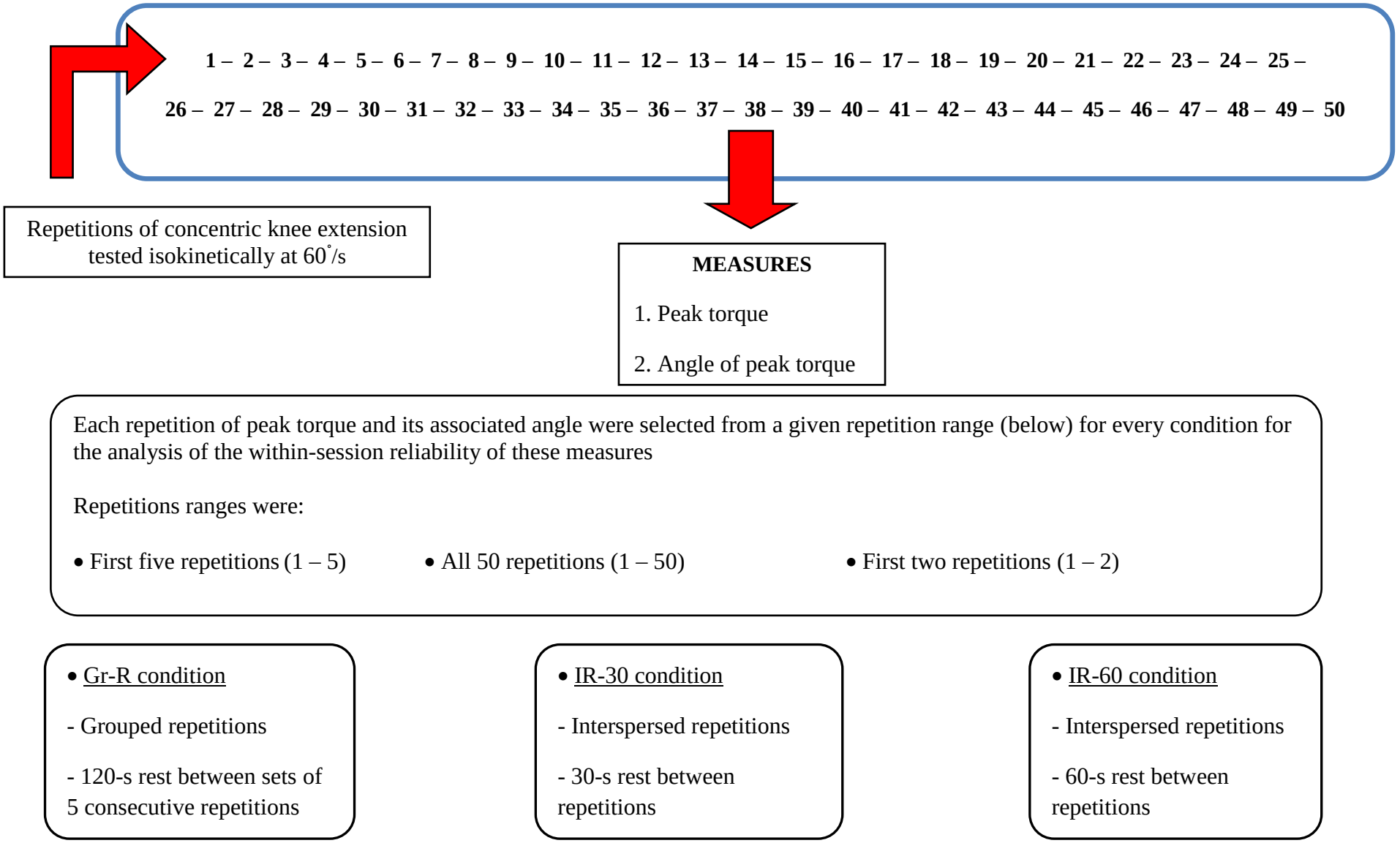


Figure 4. Peak torque and angle of peak torque data selected for analysis of within-session reliability

Chapter 4 - Results

4.1 Participants characteristics

Twenty-four young adult male participants completed testing. They all undertook at least 120 min of exercise training per week, but were heterogeneous with regard to their volume of resistance training (table 3). Participant's muscle soreness was consistent between sessions and was within the 2cm VAS cut off, except for P15 whose muscle soreness (accrued from own exercise) was too high to complete their second testing session (IR-60). Consequently this session was delayed three days for their muscle soreness to return to baseline levels.

Table 3. Participants' descriptive data (mean ± SD (range)).

(n = 24)	
Age (y)	22.7 ± 3.1 (18.5 – 29.3)
Height (cm)	182.4 ± 8.6 (164.7 – 198.3)
Body mass (kg)	77.9 ± 7.9 (63.5 – 99.2)
Minutes of resistance training per week	180 ± 177 (0 – 840)
Minutes of training per week	400 ± 200 (120 – 900)

4.2 Within-session reliability of peak torque and its angle

The majority of isokinetic testing has traditionally used grouped repetitions of knee extension and flexion in a reciprocal movement (Chan et al., 1996). During grouped repetitions muscular fatigue may occur, possibly resulting in inconsistent values of angle of peak torque. Also problematic is that the within-subject variation of peak torque and its angle are not often considered within isokinetic strength testing despite the popularity of this testing method. Previous reliability studies are inconclusive as to the within-session reliability of angle of peak torque. Due to the mixed findings and inconsistent methods of previous reliability studies it is unknown how many repetitions it may take to achieve a reliable angle of peak torque or if it actually becomes reliable with repeated contractions. Therefore multiple interspersed and grouped repetitions of isokinetic knee extension were chosen for the current study in order to explore the within-session reliability of peak torque and its angle.

4.2.1 What is the reliability of peak torque and its angle over the first five repetitions?

The mean peak torque and its angle for grouped and interspersed protocols over the first five repetitions of concentric knee extension are presented in table 4, along with parameters of their reliability. All three conditions had similarly moderate Standard Error of Measurement (SEM), Minimal Detectable Change (MDC) and high Intraclass Correlation Coefficient (ICC) for peak torque. The SEM of angle of peak torque was similarly low between protocols and the MDC was moderate, however it's ICC was low over the first five repetitions for all protocols. Additionally, the MDC of peak torque and its angle was within an acceptable range. The criteria for a reliable SEM and acceptable range of MDC in the current study was: (i) Peak torque = SEM ≤ 15 N.m, SEM% ≤ 6%, MDC ≤ 40 N.m, MDC% ≤ 18% (ii) Angle of peak torque = SEM ≤ 5°, SEM% ≤ 6%, MDC ≤ 12°, MDC% ≤ 18%. This criteria was based on the same reasoning as that outlined in the review of literature (Section 2.18 of Chapter 2).

Table 4. Within-session reliability of peak torque and its angle for grouped and interspersed protocols over the first five repetitions of concentric knee extension tested isokinetically at 60°/s

	Peak torque						Angle of peak torque					
Condition	**Mean ± SD (N.m)**	**SEM (N.m)**	**MDC (N.m)**	**SEM %**	**MDC %**	**ICC (95% CL)**	**Mean ± SD (°)**	**SEM (°)**	**MDC (°)**	**SEM %**	**MDC %**	**ICC (95% CL)**
Gr-R	221 ± 39	12	34	6	15	0.90 (0.83 – 0.95)	69 ± 7	4	12	6	17	0.59 (0.41 – 0.76)
IR-30	232 ± 44	10	29	4	12	0.95 (0.90 – 0.97)	72 ± 6	4	11	5	15	0.53 (0.35 – 0.72)
IR-60	237 ± 39	12	33	5	14	0.91 (0.84 – 0.95)	70 ± 6	3	9	4	12	0.73 (0.59 – 0.85)

Abbreviations: SEM = raw or absolute Standard Error of Measurement; MDC = Minimal Detectable Change; SEM % = SEM as a percentage of the group mean; MDC % = MDC as a percentage of the group mean; ICC = Intraclass correlation coefficient; Gr-R = grouped repetitions; IR-30 = repetitions interspersed by 30-s; IR-60 = repetitions interspersed by 60-s

4.2.2 What are the minimum repetitions to obtain a reliable peak torque?

The mean peak torque for grouped and interspersed protocols over the first two repetitions of concentric knee extension are presented in table 5, as well as its reliability statistics. When repetitions were interspersed or grouped the first two knee extensions demonstrated moderate SEM (< 6%), acceptable MDC (< 35 N.m) and high ICCs (> 0.90) regardless of the condition performed.

Table 5. Within-session reliability of peak torque for grouped and interspersed protocols over the first two repetitions of concentric knee extension tested isokinetically at 60˚/s

Condition	Mean ± SD (N.m)	SEM (N.m)	MDC (N.m)	SEM%	MDC%	ICC (95% CL)
Gr-R	215 ± 39	12	33	6	15	0.91 (0.80 – 0.96)
IR-30	224 ± 46	10	30	5	14	0.94 (0.88 – 0.98)
IR-60	227 ± 39	13	35	6	15	0.90 (0.77 – 0.93)

Abbreviations: see table 4

4.2.3 What are the minimum repetitions to obtain a reliable angle of peak torque?

The mean angle of peak torque and parameters of its reliability for interspersed protocols over the first two repetitions of concentric knee extension are presented in table 6. The minimum number of grouped repetitions to obtain a reliable angle of peak torque is five (table 4).

Table 6. Within-session reliability of angle of peak torque for interspersed protocols over the first two repetitions of concentric knee extension tested isokinetically at 60˚/s

Condition	Mean ± SD (˚)	SEM (˚)	MDC (˚)	SEM%	MDC%	ICC (95% CL)
IR-30	72 ± 6	4	11	6	15	0.54 (0.18 – 0.77)
IR-60	71 ± 6	4	10	5	14	0.62 (0.30 – 0.82)

Abbreviations: see table 4

4.2.4 What is the reliability of peak torque and its angle over all 50 repetitions?

The mean peak torque and its angle for grouped and interspersed protocols over all 50 repetitions of concentric knee extension are presented in table 7, along with measures of their reliability. All three patterns of contractions had similarly low SEM%, moderate MDC% and high ICCs for peak torque across 50 repetitions. There was no major difference in the reliability of angle of peak torque when repetitions were interspersed or grouped, although the ICC of angle of peak torque was low for all conditions. Peak torque and its angle were also reliable between repetition ranges 1 – 10, 1 – 15, 1 – 20, 1 – 25, 1 – 30, 1 – 35, 1 – 40 and 1 – 45.

Table 7. Within-session reliability of peak torque and angle of peak torque for grouped and interspersed protocols over all 50 repetitions of concentric knee extension tested isokinetically at 60˚/s

	Peak torque						Angle of peak torque					
Condition	**Mean ± SD (N.m)**	**SEM (N.m)**	**MDC (N.m)**	**SEM %**	**MDC %**	**ICC (95% CL)**	**Mean ± SD (˚)**	**SEM (˚)**	**MDC (˚)**	**SEM %**	**MDC %**	**ICC (95% CL)**
Gr-R	231 ± 36	14	39	6	17	0.84 (0.76 – 0.91)	68 ± 6	4	10	5	15	0.64 (0.51 – 0.78)
IR-30	242 ± 41	15	40	6	17	0.87 (0.80 – 0.93)	71 ± 6	3	9	5	13	0.64 (0.51 – 0.78)
IR-60	243 ± 40	13	37	6	15	0.89 (0.83 – 0.94)	71 ± 5	3	9	4	12	0.68 (0.56 – 0.81)

Abbreviations: see table 4

4.3 Peak torque and its angle over 50 repetitions

4.3.1 Raw peak torque and its angle for repetitions one to fifty

Peak torque and its angle produced by participants P7 and P8 during 50 grouped (Gr-R) and interspersed (IR-30 and IR-60) repetitions of concentric knee extension tested isokinetically at 60°/s are shown in figures 5 and 6 respectively. P7 and P8 data was extracted to show the individual differences in the magnitude and consistency of peak torque and its angle over 50 isokinetic repetitions. Peak torque for P7 during Gr-R gradually increased until the 27th repetition where its maximum of 289 N.m was attained. From repetition 27 to 50 peak torque for Gr-R gradually declined. Peak torque for both IR-30 and IR-60 gradually increased over the 50 repetitions for P7. P7 produced their highest peak torque on the 50th repetition for IR-30 and IR-60, achieving 298 N.m and 303 N.m respectively. The angle of peak torque produced by P7 for Gr-R ranged from 68° – 78°, with their highest angle produced earlier in the repetition count of each set. Their angle of peak torque for IR-30 ranged from 67° – 76° with large fluctuations over the first 15 repetitions. The angle of peak torque produced by P7 for IR-60 ranged from 64° – 73° with it gradually increasing over the 50 repetitions.Peak torque for P8 during Gr-R gradually increased until the 32nd repetition where its maximum of 255 N.m was attained. Peak torque produced by P8 for IR-30 gradually increased over the first 17 repetitions, with the highest peak torque of 268 N.m produced on the 17th repetition. However, from the 17th repetition onwards peak torque slightly declined. P8 produced their highest peak torque during IR-60 at the 9th repetition attaining 269 N.m. However, from this point onwards peak torque for IR-60 gradually declined over the 50 repetitions. The angle of peak torque produced by P8 for Gr-R ranged from 48° – 73°, with their lowest angle primarily produced later in the repetition count of each set. Their angle of peak torque for IR-30 and IR-60 ranged from 55° – 73°. However, for IR-30 it gradually decreased over the 50 repetitions, whereas for IR-60 it gradually increased after an initial and rapid decline.

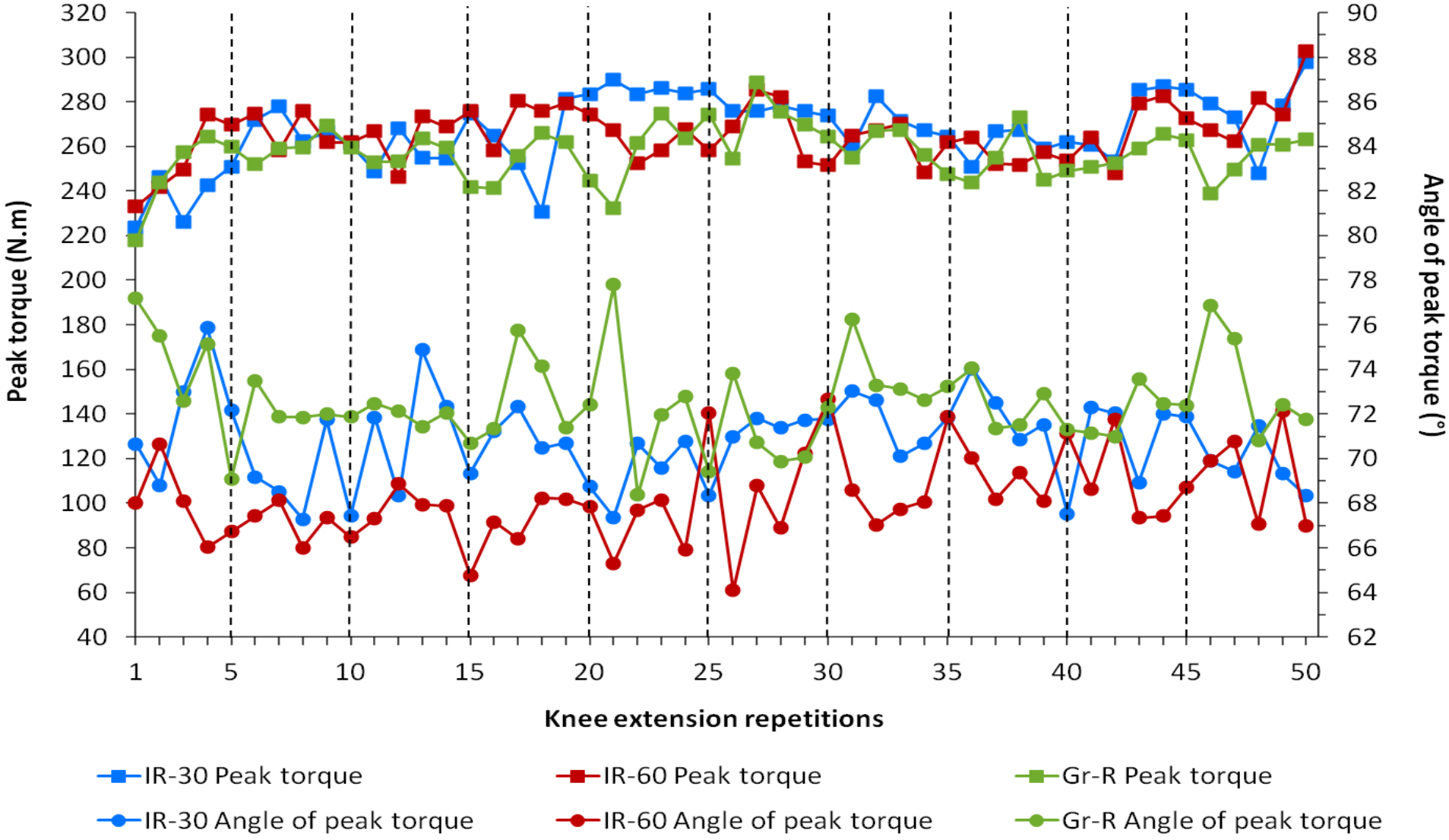


Figure 5. Peak torque and its angle produced by participant P7 for all 50 repetitions of concentric knee extension tested isokinetically at 60°/s

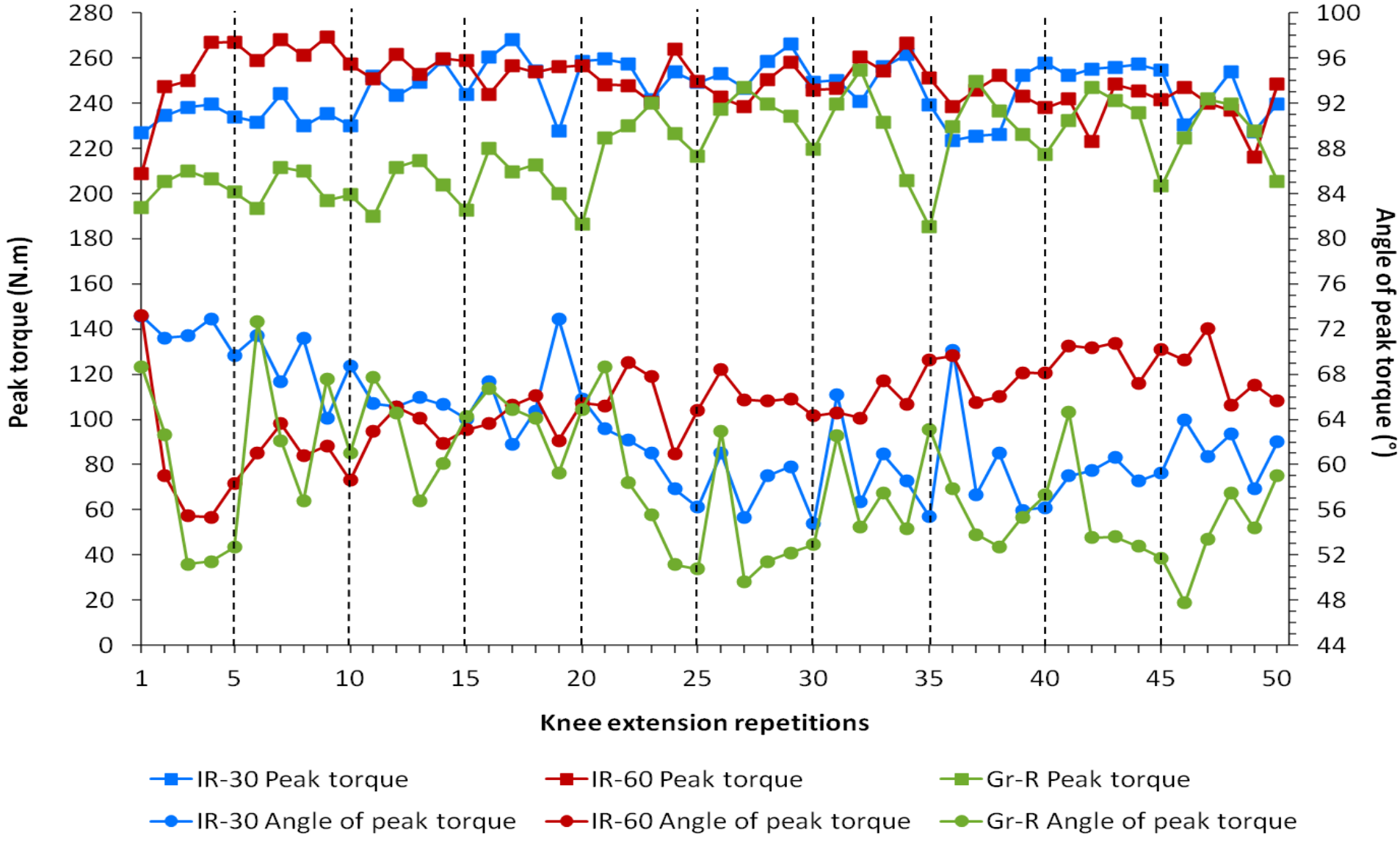


Figure 6. Peak torque and its angle produced by participant P8 for all 50 repetitions of concentric knee extension tested isokinetically at 60°/s

4.3.2 Mean peak torque of 50 repetitions

Mean peak torque over all 50 repetitions of concentric knee extension depended on the temporal pattern of contractions ($p = 0.001$), with it being lower in the Gr-R protocol (231 N.m) than in IR-60 (243 N.m; $p = 0.001$) and IR-30 (242 N.m; $p = 0.008$) protocols. The interspersed protocols produced an equivalent mean peak torque ($p = 0.988$).

4.3.3 Variability of the highest peak torque over repetitions

For the cohort as a whole, the highest peak torque was not obtained within the first five contractions, irrespective of the protocol performed (Figure 7). Thus, strength, defined as the maximal force generated by a muscle or muscle group, was not obtained within the standard testing protocol of five repetitions (Gr-R), even when repetitions were spaced 30 or 60-s apart (IR-30 and IR-60). In fact, the highest peak torque obtained using 50 repetitions was an average 11%, 10% and 7% higher than that obtained using the first five repetitions for Gr-R, IR-30 and IR-60 respectively.

So when was maximal strength obtained? When testing knee extensor strength using only the first five concentric repetitions, the highest peak torque was produced at the 3rd repetition for Gr-R, and the 4th repetition for IR-30 and IR-60, for the cohort on average. However, when using all 50 repetitions, the highest peak torque was produced at the 23rd repetition for Gr-R, 27th repetition for IR-30 and the 22nd repetition for IR-60, on average. Individual differences are described in section 4.4 below.

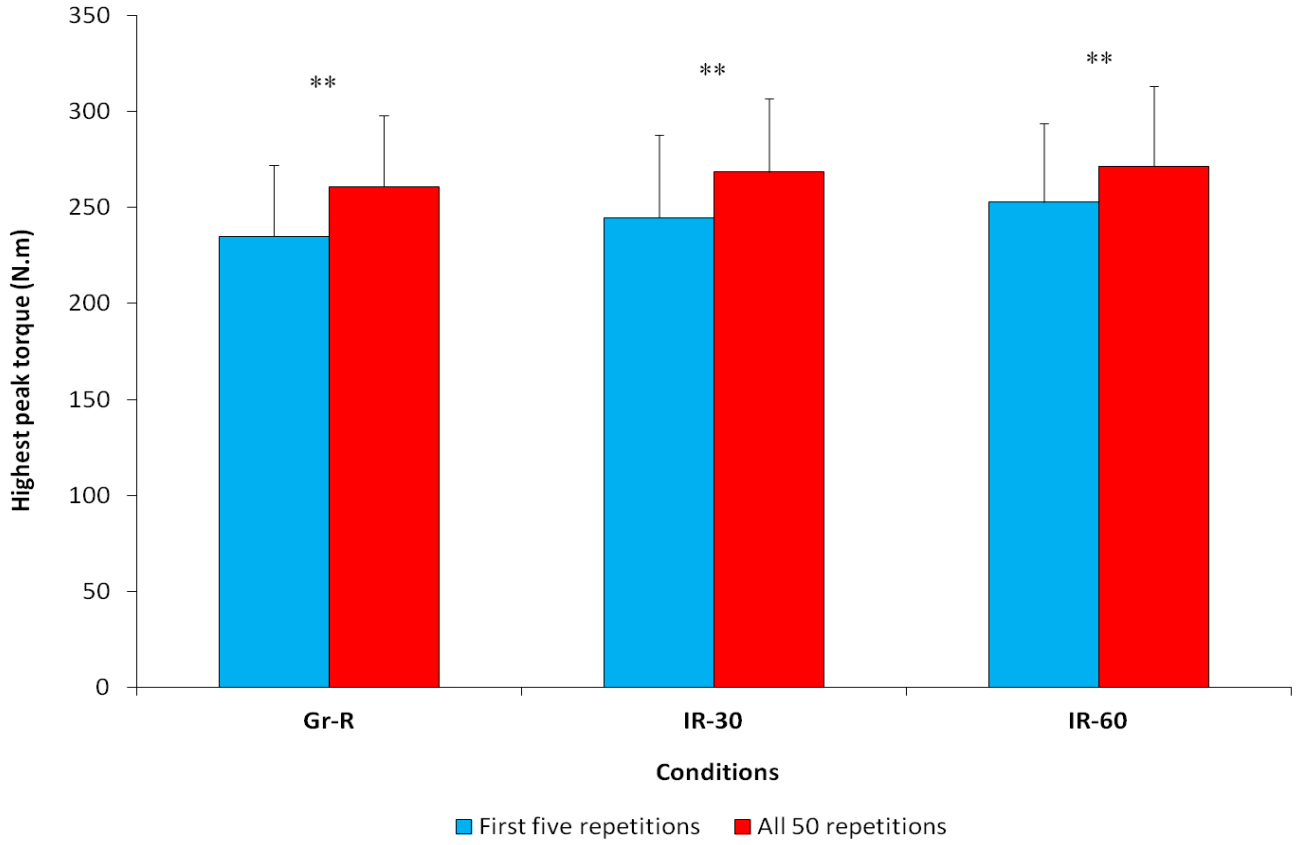


Figure 7. Highest peak torque over the first five repetitions[1] and all 50 repetitions[2] of concentric knee extension tested isokinetically at 60°/s using grouped and interspersed protocols

([1,2] data selected = [1] highest peak torque of repetitions one to five; [2] highest peak torque of all 50 repetitions)

** Significant difference between the highest peak torque of all 50 repetitions and the highest peak torque of the first five repetitions, p = 0.00

The SEM, MDC, SEM%, MDC% and ICCs of the highest peak torque over all 50 repetitions for the three conditions are presented in table 8. The parameters were calculated using the highest peak torque for each participant and the two repetitions which immediately preceded and followed this value. Using these five consecutive repetitions for each participant, all three conditions showed reliable within-session SEM and SEM% values for peak torque (≤ 15 N.m, ≤ 6%), as well as an acceptable range of MDC and MDC% values for peak torque (≤ 40 N.m, ≤ 18%) during concentric knee extension tested isokinetically at 60°/s.

Table 8. Within-session reliability of the highest peak torque over all 50 repetitions for grouped and interspersed protocols during concentric knee extension tested isokinetically at 60˚/s

Condition	Mean ± SD (N.m)	SEM (N.m)	MDC (N.m)	SEM%	MDC%	ICC (95% CL)
Gr-R	242 ± 38	10	27	4	11	0.94 (0.89 – 0.97)
IR-30	256 ± 38	10	28	4	11	0.93 (0.88 – 0.97)
IR-60	258 ± 39	10	28	4	11	0.94 (0.89 – 0.97)

Abbreviations: see table 4

4.3.4 Variability of the angle at the highest peak torque over repetitions

As shown in figure 8, the angle of the knee extensors at the highest peak torque for the first five repetitions was 2% higher than during all 50 repetitions of concentric knee extension for Gr-R and IR-30. These differences were not significant, p = 0.06 and 0.17 for Gr-R and IR-30 respectively. There was no difference in the angle of the knee extensors at the highest peak torque between the first five repetitions and all 50 repetitions for IR-60.

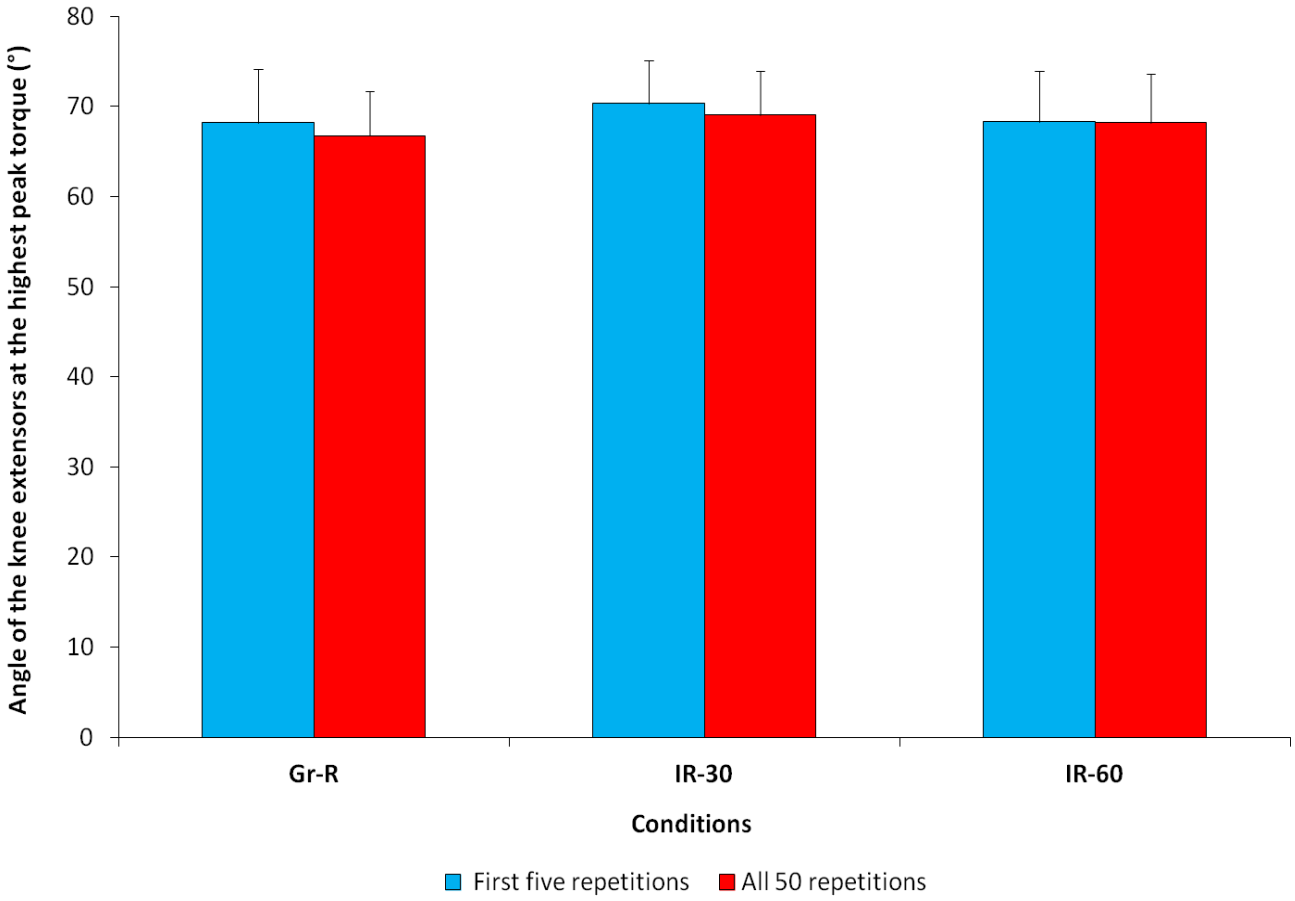


Figure 8. Angle at the highest peak torque over the first five repetitions[1] and all 50 repetitions[2] of concentric knee extension tested isokinetically at 60°/s using grouped and interspersed protocols

([1, 2] data selected = [1]angle at the highest peak torque of repetitions one to five; [2]angle at the highest peak torque of all 50 repetitions)

The SEM, MDC, SEM%, MDC% and ICCs of the angle of the knee extensors at the highest peak torque over all 50 repetitions for the three conditions are presented in table 9. The parameters were calculated using the angle at the highest peak torque for each participant and the two repetitions which immediately preceded and followed this value. Using these five consecutive repetitions for each participant, all three conditions showed reliable within-session SEM and SEM% values for the angle of knee extensors at the highest peak torque ($\leq 5^{\circ}$, $\leq 6\%$), as well as an acceptable range of MDC and MDC% values for the angle at the highest peak torque ($\leq 12^{\circ}$, $\leq 18\%$) during concentric knee extension tested isokinetically at 60°/s.

Table 9. Within-session reliability of the angle at the highest peak torque over all 50 repetitions for grouped and interspersed protocols during concentric knee extension tested isokinetically at 60°/s

Condition	Mean ± SD (°)	SEM (°)	MDC (°)	SEM%	MDC%	ICC (95% CL)
Gr-R	70 ± 5	2	6	3	9	0.79 (0.66 – 0.89)
IR-30	69 ± 6	2	6	3	9	0.84 (0.73 – 0.92)
IR-60	67 ± 5	3	8	4	11	0.73 (0.59 – 0.85)

Abbreviations: see table 4

4.3.5 Mean peak torque and its angle for repetitions one to fifty

As shown in figure 9, mean peak torque and angle of peak torque are variable for all conditions across 50 repetitions of concentric knee extension tested isokinetically at 60°/s. The grouped repetition protocol (Gr-R) achieved its highest mean peak torque of 243 N.m at the 12th repetition. Besides the first repetition, Gr-R consistently achieved its highest mean peak torque on the second or third repetition of every set of five repetitions. It also achieved its lowest mean peak torque on the fifth (last) repetition of every set, except for the first set.

Mean peak torque for repetitions interspersed by 30-s (IR-30) gradually increased over the first 17 repetitions then plateaued before achieving its highest mean peak torque of 240 N.m at the 50th repetition. Over the first nine repetitions mean peak torque of interspersed repetitions with a 60-s rest (IR-60) increased sharply, reaching its highest mean peak torque of 252 N.m at the ninth repetition. From repetition 10 onwards mean peak torque of IR-60 gradually decreased until it increased on the last few repetitions.

Gr-R consistently achieved its highest mean angle of peak torque on the first repetition of every set of five repetitions. It also achieved its lowest mean angle of peak torque on either the fourth or fifth repetition of every set of 5 repetitions, except for the last two sets where it achieved it on the third repetition.

Mean angle of peak torque for IR-30 initially increased over the first three repetitions then rapidly decreased. From repetitions 6 to 50 it fluctuated considerably within a small range. Mean angle of peak torque for IR-60 decreased rapidly over the first four repetitions. From repetition 5 to 50 it gradually increased. Overall mean angle of peak torque for IR-60 trended upwards over the 50 repetitions.

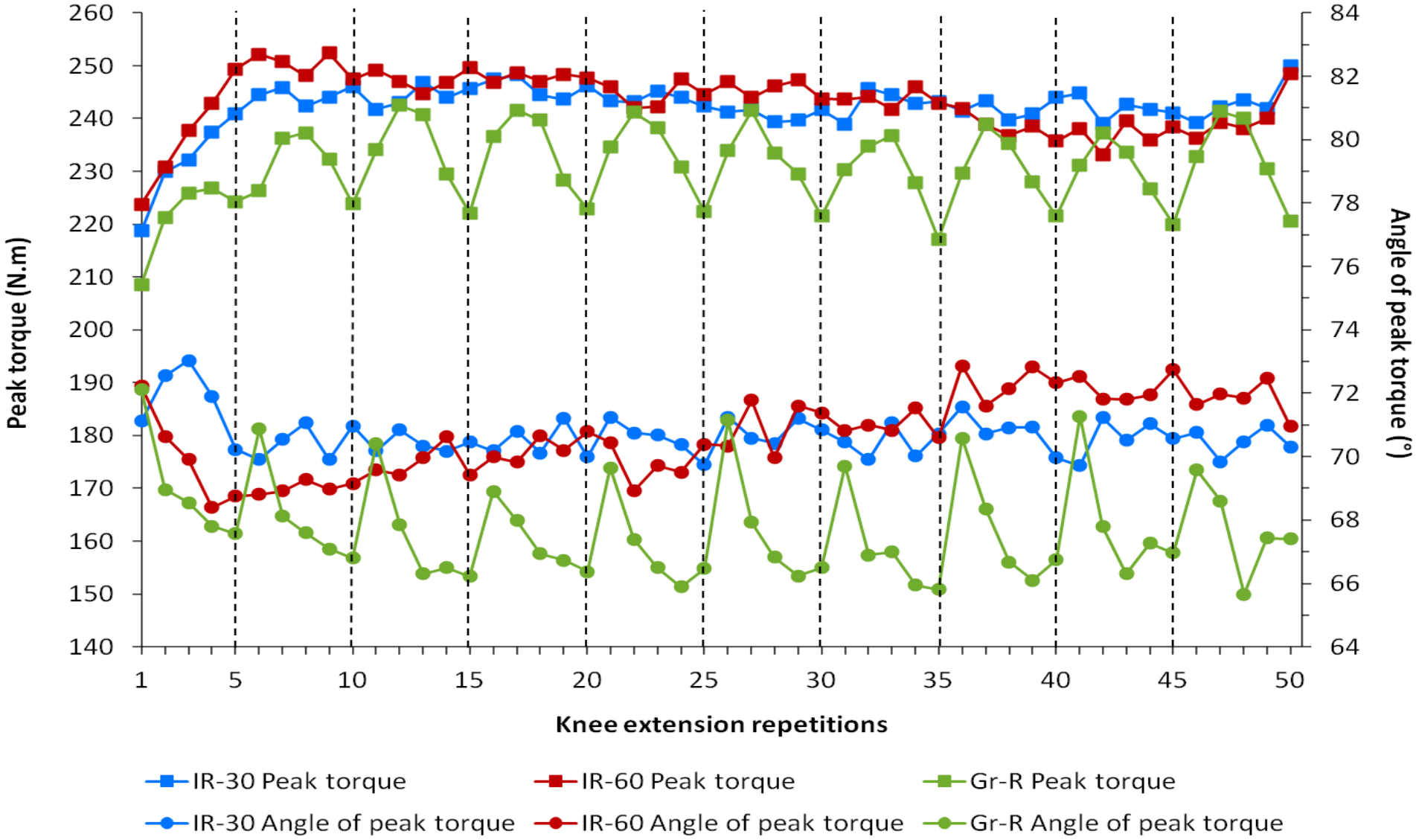


Figure 9. Mean peak torque and angle of peak torque for all 50 repetitions of concentric knee extension tested isokinetically at 60°/s for grouped and interspersed protocols

4.4 Repetitions at which the highest peak torque was obtained

4.4.1 Percentage of participants that obtained their highest peak torque over given repetition ranges

As shown in figure 10 below, 38% of participants achieved their highest peak torque between repetitions 11-20 and 1-10 for grouped repetitions and interspersed repetitions with a 60-s rest respectively. One third of participants obtained their highest peak torque between repetitions 41-50 for interspersed repetitions with a 30-s rest.

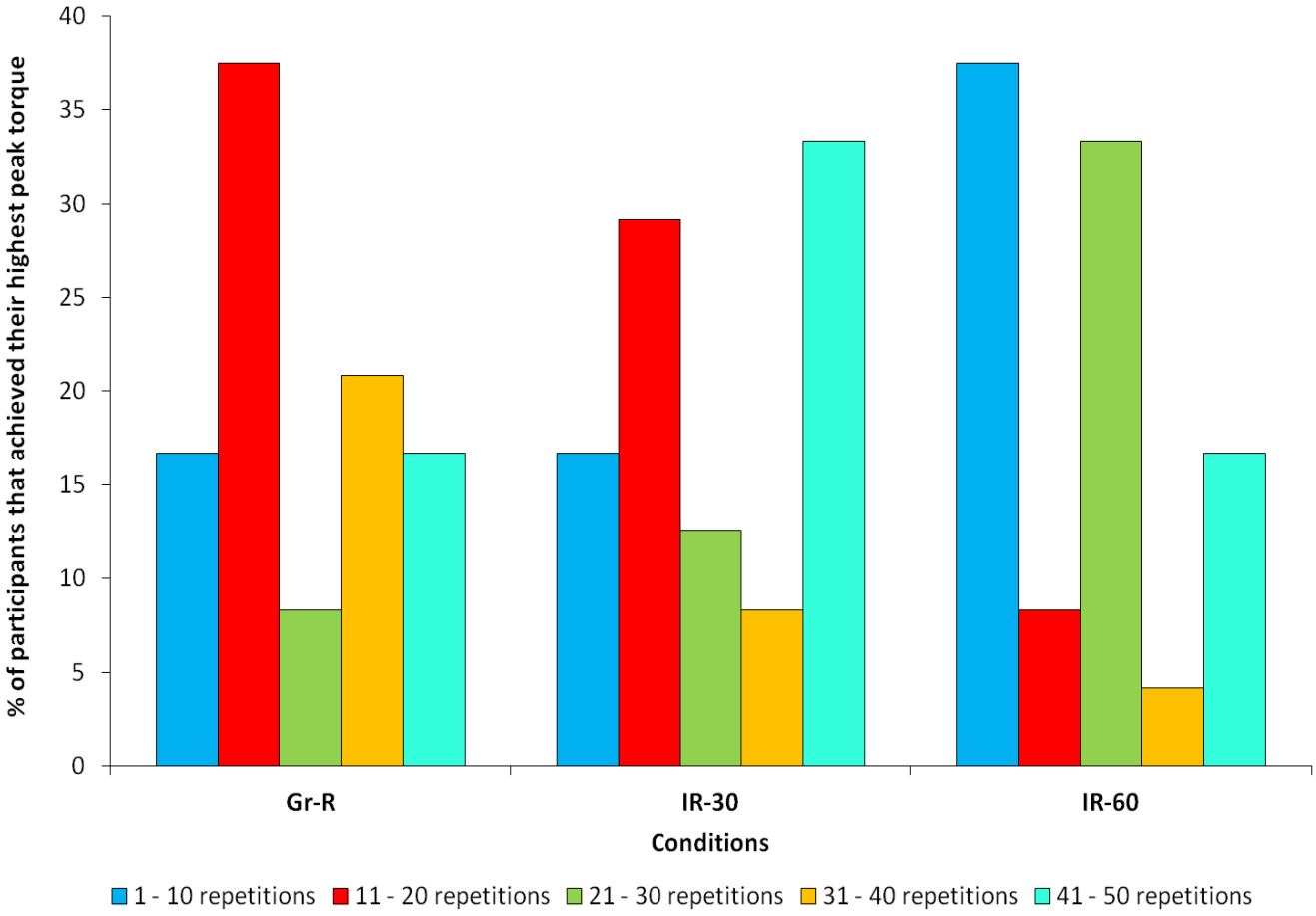


Figure 10. Percentage of participants that achieved their highest peak torque over knee extension repetitions 1 – 10, 11 – 20, 21 – 30, 31 – 40 and 41 – 50 for grouped and interspersed protocols

4.4.2 Repetitions at which participants obtained their highest peak torque

As shown in figure 11 below, the repetition at which the highest peak torque was obtained for grouped and interspersed protocols varied between most participants. Participants that had a similar highest peak torque for grouped and interspersed protocols were: P9 and P28; P24, P8 and P4; P21 and P29; P14 and P19; P26 and P25. Besides these similarities there were no obvious trends. In figure 11 participants are placed in order based upon the protocol and the repetition with which they achieved their highest peak torque. Participants are ordered (left to right) from the highest to lowest repetition for each protocol, starting with grouped repetitions then interspersed repetitions.

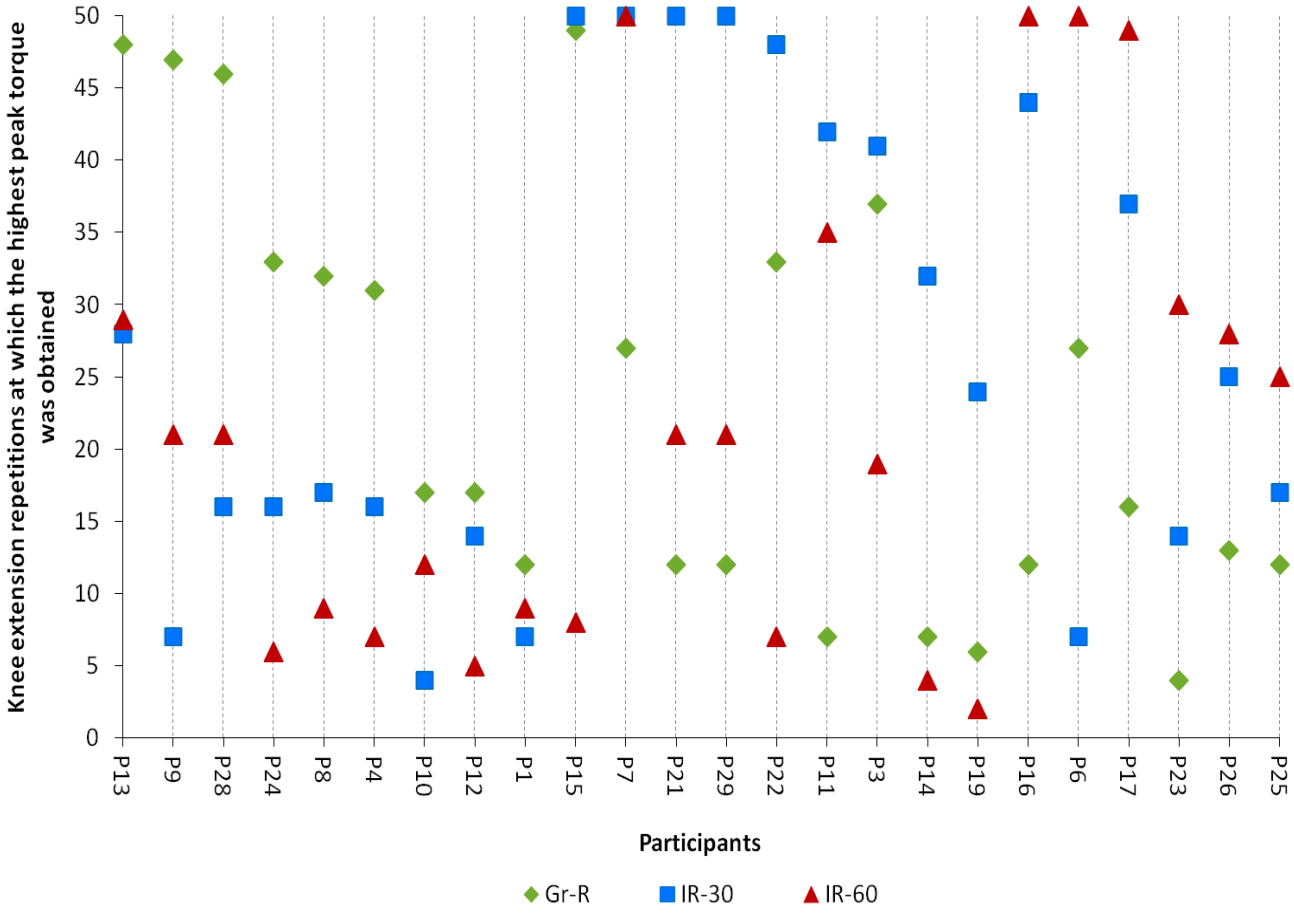


Figure 11. Repetitions at which each participant obtained their highest peak torque for grouped and interspersed protocols during concentric knee extension tested isokinetically at 60°/s

Participants P9 and P28 had a similar body mass and they both came from endurance running backgrounds. However, their total minutes of training differed. P8 and P4 also had a similar body mass however the body mass of P24 differed. Although the total minutes of training were similar for P24 and P8. P21 and P29 both had a similar body mass, training background and total minutes of training. This was also the case for P19 and P14, and P25 and P26.

4.5 Participant covariates

Training volume did not influence peak torque or angle of peak torque across the cohort. Specifically, minutes of resistance training per week did not significantly affect mean peak torque ($p = \geq 0.29$ for each of the three conditions) or mean angle of peak torque ($p = \geq 0.364$). Neither did minutes of overall training per week affect mean peak torque ($p = \geq 0.901$) and mean angle of peak torque ($p = \geq 0.219$). Participant's body mass also did not significantly affect mean angle of peak torque ($p = \geq 0.163$ for each of the three conditions). However, participant's body mass did significantly affect mean peak torque ($p = \leq 0.01$ for each of the three conditions).

As participants body mass affected mean peak torque, peak torque was expressed relative to body mass as a standard error of measurement and minimal detectable change (SEM peak torque (N.m) per kg and MDC peak torque (N.m) per kg). There was no adjustment of peak torque when standardising by body mass. Relative SEM and MDC values (peak torque (N.m) per kg) expressed as a percentage of the group mean were firstly compared to absolute SEM and MDC values expressed as a percentage of the group mean in order to see if any difference existed between these data sets. As shown in table 10 the absolute and relative SEM and MDC values expressed as a percentage of the group mean for each condition are very similar over first five repetitions (1 – 5) and all 50 repetitions (1 – 50) of concentric knee extension. The relative and absolute SEM and MDC values expressed as a percentage of the group mean for

each condition were also very similar across all other groups of repetitions analysed including 1-10, 1-15, 1-20, 1-25, 1-30, 1-35, 1-40, 1-45 repetition groups. Only two groups of repetitions comparing relative and absolute SEM and MDC values expressed as a percentage of the group mean are shown in table 10 as all other groups of repetitions had similar absolute and relative SEM and MDC values. Due to the similarity between the absolute and relative SEM and MDC values expressed as a percentage of the group mean only the absolute SEM and MDC values are of interest and will only be shown in the dichotomised data section.

Table 10. Absolute and relative Standard Error of Measurement and Minimal Detectable Change of peak torque for grouped and interspersed protocols for the first five and all 50 repetitions of concentric knee extension tested isokinetically at 60˚/s

Conditions and repetitions	Absolute SEM %	Relative SEM % (Peak torque (N.m) per kg)	Absolute MDC %	Relative MDC % (Peak torque (N.m) per kg)
Gr-R: reps 1 – 5	6	6	15	15
IR-30: reps 1 – 5	4	5	12	13
IR-60: reps 1 – 5	5	5	14	13
Gr-R: reps 1 – 50	6	6	17	17
IR-30: reps 1 – 50	6	6	17	17
IR-60: reps 1 – 50	6	6	15	15

Abbreviations: see table 4

4.6 Dichotomised peak torque data

Peak torque and angle of peak torque data over all 50 repetitions of concentric knee extension for all 24 participants were dichotomised into low and high subgroups for each condition based on body mass, minutes of resistance training and minutes of training per week, and mean peak torque. Twelve participants with the highest body mass, minutes of resistance training and training per week, and mean peak torque were assigned into the high sub group and the other 12 participants were assigned into the low sub group. This was done to identify

if whether SEM and MDC differed with body mass, strength, or resistance training load. As stated above in the covariates section, the absolute and relative SEM and MDC values expressed as a percentage of the group mean were very similar across all groups of repetitions. This was also the case for the dichotomised absolute and relative SEM and MDC values of peak torque expressed as a percentage of the group mean when comparing the same subgroups such as IR-30 peak torque – high – body mass. In addition to this if differences existed between low and high subgroups of mean peak torque, body mass, minutes of resistance training or minutes of training for the absolute SEM and MDC values expressed as a percentage of the group mean this difference was also similar in the relative SEM and MDC values. As the relative and absolute SEM and MDC values when expressed as a percentage of the group mean were similar for the dichotomised data only the absolute SEM and MDC values are of interest and are shown in table 11. The data displayed in table 11 are for the conditions which showed the largest difference in SEM and MDC of peak torque between low and high sub groups. All other subgroups for peak torque and angle of peak torque had similar SEM and MDC values. As shown in table 11, participants who had a higher body mass for IR-30, produced a lower level of peak torque for IR-60 and trained for more minutes for Gr-R had a lower and more reliable SEM and SEM%, and a lower MDC and MDC% of peak torque compared to their opposed subgroup.

Table 11. Dichotomised peak torque data for interspersed and grouped protocols over all 50 repetitions of concentric knee extension tested isokinetically at 60˚/s (n = 12 participants for each high and low subgroup)

Condition	Subgroup	Mean ± SD (N.m)	SEM (N.m)	MDC (N.m)	SEM %	MDC %	ICC (95% CL)
IR-30	Body mass - High	251 ± 47	13	37	5	15	0.92 (0.85 – 0.97)
IR-30	Body mass - Low	234 ± 33	16	44	7	19	0.77 (0.62 – 0.91)
IR-60	Mean PT - High	274 ± 28	15	40	5	15	0.74 (0.58 – 0.89)
IR-60	Mean PT - Low	213 ± 22	12	34	6	16	0.70 (0.53 – 0.87)
Gr-R	Mins Train - High	229 ± 33	13	37	6	16	0.83 (0.71 – 0.93)
Gr-R	Mins Train - Low	251 ± 47	17	46	7	19	0.86 (0.75 – 0.95)

Abbreviations: see table 4

Chapter 5 - Discussion

5.1 Introduction to the chapter

Muscular performance is commonly assessed using isokinetic dynamometry in a variety of research, rehabilitation and exercise training settings. Peak torque and angle of peak torque measurements are the basis for making clinical decisions and interpreting the impact of research interventions. Current isokinetic testing assumes that: (i) angle of peak torque is reliably measured (Brockett et al. 1999; Brockett et al. 2001; Bowers, Morgan and Proske, 2004; Brughelli, Cronin and Nosaka, 2010a; Brughelli et al., 2010b), (ii) the torque-angle relationship is a static phenomenon and also represents sarcomere length (Brockett et al. 1999; Brockett et al. 2001) (iii) the force output and behaviour of skeletal muscle is constant from one repetition to another (Brown, 2000; Chan et al., 1996; Brockett et al. 1999; Brockett et al. 2001), and (iv) the highest peak torque is achieved within 2 – 6 grouped repetitions (Baltzopoulos & Brodie, 1989; Brown & Weir, 2001; Johnson & Siegel, 1978; Sawhill, Bates, Osternig & Hamill, 1982). While previous research has explored test-retest reliability, no previous research has been undertaken to investigate the consistency of peak torque and angle of peak torque across multiple grouped and interspersed repetitions. The present study explored these variables across 50 knee extension repetitions, with repetitions grouped or interspersed with passive recovery.

As discussed in Chapter 1, the purpose of this thesis was to *examine the within-session reliability of peak torque and angle of peak torque during concentric knee extension tested isokinetically at 60°/s across three different repetition protocols (Gr-R, IR-30 and IR-60).*

The objectives were:

To describe the Standard Error of Measurement (SEM) and Minimal Detectable Change (MDC) of peak torque and angle of peak torque within a session during concentric knee extension tested isokinetically at 60°/s across (i) a grouped repetition protocol, and (ii) interspersed repetition protocols.

Five hypotheses ($\mathbf{H_1}$ – $\mathbf{H_5}$) were outlined in Chapter 1. Peak torque production was reliable for Gr-R, thus $\mathbf{H_1}$ is supported. The angle at which peak torque was produced was reliable for Gr-R, thus $\mathbf{H_2}$ is not supported. Peak torque production was reliable for interspersed repetitions, thus $\mathbf{H_3}$ is supported. The angle at which peak torque was produced was reliable for interspersed repetitions, thus $\mathbf{H_4}$ is supported. Peak torque production was higher ($p < 0.01$) for interspersed repetitions than grouped repetitions over all 50 repetitions of concentric knee extension tested isokinetically at 60°/s, thus $\mathbf{H_5}$ is supported.

A secondary aspect of this thesis was also to explore and describe peak torque and its angle over 50 repetitions of concentric knee extension tested isokinetically at 60°/s across grouped and interspersed repetition protocols.

5.2 Within-session reliability of peak torque and its angle

In the current study peak torque and its angle were deemed reliable and within an acceptable range of MDC based on: (i) that reported in the literature (Hartmann et al., 2009; Sole et al., 2007), and (ii) the magnitude of change in strength from given interventions (Van Roie et al., 2013). For further details as to what is deemed a reliable measure of peak torque and angle of peak torque, and what is an acceptable MDC for these measures refer to subsection *4.2.1* of Chapter 4. The reliability of peak torque and its angle in the current study were assessed primarily using SEM, rather than relying on Intraclass Correlation Coefficient (ICCs) and MDC. SEM was used as primary measure of reliability as it indicates the within-subject variation of peak torque and its angle. Most studies (Maffiuletti et al., 2007; Capranica et al., 1998; Sole et al., 2007; Ayala et al., 2012; Bernard et al., 2012; Phillips et al., 2000) use an average or the highest peak torque and its angle for data analysis. In the current study every repetition of peak torque and its angle were used in analyses, and this may have provided a better indication of the reliability of these measures as every raw data point was captured.

5.2.1 Reliability of peak torque over the first five repetitions

Peak torque was shown to be reliable within a session over the first five repetitions of concentric knee extension for all conditions, with the SEM ranging between 10 and 12 N.m. Additionally, MDC was within an acceptable range (≤ 40 N.m, ≤ 18%) for all conditions, and the ICC of peak torque was very high (0.90 – 0.95). In comparison to the current study Stratford et al. (1990) found similar ICCs for peak torque within a session over five grouped and interspersed repetitions, as did Harding et al. (1988) over six interspersed repetitions. However, the SEM of peak torque reported by Stratford et al. (1990) was lower than the current study, and they found a difference in their SEM between interspersed and grouped repetitions. This could be due to Stratford et al. (1990) analysing the average peak torque of all five repetitions, as well as using a different SEM calculation.

In general peak torque has previously been shown to be reliable within a session using ICCs and SEM over the first five grouped and interspersed repetitions of concentric knee extension when tested isokinetically at 60°/s. The findings from the current study agree with previous studies, although the SEM of the current study does slightly differ to that found in previous studies. The reliability of peak torque over the first five repetitions in the current study suggests that muscle properties or other factors affecting peak torque become or are consistent over these repetitions otherwise a larger SEM and MDC of peak torque would have been detected. Although peak torque is variable from one repetition to another its fluctuations are not great enough to cause it to be unreliable. Participant motivation and concentration may also be high within the first several repetitions which could also result in a consistent torque production. It could be concluded that peak torque is a robust measure during concentric isokinetic knee extension as it has previously been reliably tested within and between sessions at 60°/s even though slightly different methods have been employed, and different data sets have been selected for analysis. It could also be surmised that physically active individuals are

fairly consistent in their ability to produce peak torque over the first five repetitions. Finally, rest periods between repetitions did to not seem to improve the reliability of peak torque so maybe muscular fatigue was not as evident over the first five repetitions.

5.2.2 Reliability of angle of peak torque over the first five repetitions

Previous research on the reliability of angle of peak torque in a session has been contradictory. While some studies (using SEM and ICCs) have shown that angle of peak torque is reliable (Maffiuletti et al., 2007; Harding et al., 1988), other studies (using ICCs) have shown that it is not (Wilhite et al., 1992; Phillips et al., 2000). The current study showed that angle of peak torque for all conditions was reliable over the first five repetitions of concentric knee extension, with the SEM ranging from $3^{\circ} - 4^{\circ}$. However, the ICC of angle of peak torque ranged between 0.53 – 0.73. Wilhite et al. (1992) and Brown et al. (1993) both reported low ICCs for angle of peak torque during isokinetic knee extension. In contrast Harding et al. (1988) reported a high ICC and a low SEM for angle of peak torque over six interspersed repetitions. The current study is the only other study besides that of Maffiuletti et al. (2007) to report a low within-subject variation of angle of peak torque in a session.

There are a number of reasons why angle of peak torque may be challenging to measure reliably. A key issue is the movement of the knee axis of rotation relative to the dynamometer axis throughout the knee extension movement. Ayala et al. (2012) were one of a few studies to acknowledge this limitation and the subsequent error of using dynamometer angle to infer knee joint angle. Previous between and within-session reliability studies of knee extension have assumed that knee joint angle and dynamometer angle are the same and have not critically examined what they are measuring. This issue was carefully explored in the preliminary work of the current study (see Appendix A).

The preliminary work of the current study demonstrated that an individual's knee axis of rotation can move within a range of approximately 3.2 – 4.7 cm horizontally and 4.1 – 7 cm

vertically during knee extension from 105° to a participants end range of motion. As the knee axis centre of rotation appears to move consistently from one repetition to another during concentric knee extension, it is assumed that there is a consistent error between knee joint angle and dynamometer angle. In the absence of a suitable alternative measure of knee joint angle, dynamometer angle can be used to consistently infer knee joint angle. Using this information the current study was designed to minimise the impact of this phenomena. A specialised harness was employed to secure participants in the dynamometer chair, minimising the extraneous hip and knee axis movements during knee extension that may ultimately affect the reliability of angle of peak torque. Previous research has not used such a specialised harness during testing and the absence of this could be one possible cause of error when measuring angle of peak torque.

It was hypothesised that angle of peak torque was not going to be reliable for grouped repetitions, but might be reliable for interspersed repetitions. These hypotheses were based on the results of previous reliability studies and theoretical changes in muscle properties with grouped repetitions. It was expected that the consecutive nature of grouped repetitions and the limited rest associated with them would prevent muscle properties from stabilising and would thus result in very large fluctuations in angle of peak torque. However, the findings of the current study have shown that the reliability for angle of peak torque is similar after five grouped and interspersed repetitions. Thus muscle properties likely to affect angle of peak torque might be consistent after five grouped or interspersed repetitions. As there was no apparent difference in the reliability of angle of peak torque between grouped and interspersed protocols either of these conditions can be used to obtain reliable measures of angle of peak torque.

5.2.3 Minimum repetitions to obtain a reliable peak torque

The current study sought to identify the minimum number of repetitions required to reliably measure peak torque and its angle. This has important practical implications particularly for individuals who may lack the ability or conditioning (e.g. injured or disease populations) to perform multiple repetitions or have limited time for testing. It was found that only two grouped or interspersed repetitions of concentric knee extension tested isokinetically at 60°/s were required to achieve a reliable peak torque in a session. Previous research (Phillips et al., 2000; Wilhite et al., 1992; Maffiuletti et al., 2007) undertaken to investigate the reliability of peak torque has done so after three to four grouped repetitions. Their research also found that peak torque was reliable, which agrees with the current study.

In regards to interspersed repetitions, Ayala et al. (2012) reported a low ICC and a high CV for peak torque after two repetitions, whereas Sole et al. (2007) found high ICCs and a low SEM for peak torque after three interspersed repetitions between sessions. Previous studies have not examined the within-session reliability of peak torque over just two repetitions. As the first two grouped and interspersed repetitions are shown to be reliable in the current study only this number of repetitions are required during testing of concentric isokinetic knee extension at 60°/s within a session. As a result testing is time efficient and can be performed prior to an exercise training session.

5.2.4 Minimum repetitions to obtain a reliable angle of peak torque

Another key finding of the current study was that only five grouped repetitions and two interspersed repetitions of isokinetic knee extension at 60°/s are required to achieve a reliable angle of peak torque. Previous research by Maffiuletti et al. (2007) and Bernard et al. (2012) found angle of peak torque to be reliable over three and four grouped repetitions respectively. Whereas Phillips et al. (2000) and Ayala et al. (2012) reported angle of peak torque to be unreliable over three grouped and two interspersed repetitions respectively. Although the

studies by Maffiuletti et al. (2007) and Bernard et al. (2012) showed positive results for the reliability of angle of peak torque, most previous studies have shown that based on the SEM and ICCs reported angle of peak torque is not reliable within and between sessions.

In the current study, as five grouped and two interspersed repetitions were required to obtain a reliable angle of peak torque, this suggests for grouped repetitions that muscle properties or other factors affecting angle of peak torque may have needed time to become consistent and stable. Therefore, during repetitions one to four for the grouped protocol angle of peak torque may have fluctuated too greatly in order to obtain a reliable measure. The rest associated with interspersed repetitions may have allowed muscle properties or other factors affecting angle of peak torque to be consistent over contractions.

5.2.5 Reliability of peak torque and its angle over all 50 repetitions

The current study found peak torque and its angle to be reliable within a session over 50 repetitions of concentric isokinetic knee extension for all conditions. SEM and ICC for peak torque and its angle were similar between conditions. Additionally, MDC was within an acceptable range for peak torque ($\leq$ 40 N.m, $\leq$ 18%) and angle of peak torque ($\leq 12^{\circ}$, $\leq$ 18%). It is important to report the within-session reliability of peak torque and its angle over all 50 repetitions as peak torque increases with repetitions and individuals vary as to when they achieve their highest peak torque. Knowledge of the within-session reliability of these measures over 50 repetitions is important if future studies want to investigate the effects of different acute interventions over 50 repetitions or measure the mechanisms that cause an increase of peak torque over this repetition range.

5.3 Interpretation and utility of Standard Error of Measurement, Minimal Detectable Change and Intraclass Correlation Coefficients

The current study used three parameters of reliability: (i) SEM, (ii) MDC, and (iii) ICCs. The SEM is a form of within-subject variation and provides an estimate of how much measurement error is associated with a given measure (Safrit & Wood, 1989). MDC is the smallest amount of change required in a measure in order to detect a true change (Steffen & Seney, 2010). Scores at or above the level of MDC are 95% likely that a real change has occurred, with such scores reflecting an individuals improvement on the test (Steffen & Seney, 2010). Establishing the within-subject variation of a measure allows any changes within or between tests to be accurately tracked over time. If the within-subject variation of a measure is unknown prior to testing changes detected in a measure between tests might be meaningless. ICCs assess the amount of error associated with a measure based on the variability between subjects (Atkinson & Nevill, 1998). A large number of reliability studies (Wilhite et al., 1992; Brown et al., 1992; Kilfoil et al., 1993; Brown et al., 1993; Capranica et al., 1998; Phillips et al., 2000) report only the ICC of peak torque and angle of peak torque rather than other measures of reliability. The problem with this is that ICCs reveal between-subject variation and not how much error there is from one repetition to another for a given individual (Atkinson, 2003). Therefore this may be a limitation in the results presented by the aforementioned studies as the precision of estimates of change in peak torque and angle of peak torque are unknown, and such estimates of change are integral when monitoring such measures. SEM and MDC are better measures as they determine how much of a change in a measure is required between trials.

In the current study MDC was high relative to SEM for both peak torque and angle of peak torque for all the repetition ranges analysed. This concept has been demonstrated in figure 12 using data for the interspersed protocol with a 30-s rest over the first two repetitions, which had a mean score of 224 N.m, a SEM of 11 N.m and a MDC 30 N.m. As a hypothetical

example, say peak torque of 224 N.m is a baseline score, and testers are looking at changes in this score from an acute intervention. Using SEM and MDC as strict measures, the change in peak torque from the intervention has to be greater than 235 N.m to be above the measurement error (SEM), and greater than 254 N.m in order to see a true change (MDC). Therefore, if the difference in peak torque falls between 194 N.m and 254 N.m a true change in peak torque will probably not be seen as it is clouded by error. However, MDC is almost three times larger than SEM. In particular, if a score falls in this 19 N.m gap between the SEM of 235 N.m and the MDC of 254 N.m would this score still be confounded by measurement error? Further to this, does all of the difference between SEM and MDC (19 N.m in the example) confound a true change? SEM does seem to be within a realistic score, however MDC does seem too high to confound that much of a true change. In fact clinically significant differences could fall in the MDC range of 30 N.m as changes in peak torque greater than 20 N.m could be beneficial for an individual rehabilitating a limb after injury. With this in mind caution should be taken when interpreting MDC of the current study as true changes could be detected below the reported levels. Therefore the MDC values reported in the current study should only be used as a guideline when interpreting true changes in peak torque and its angle.

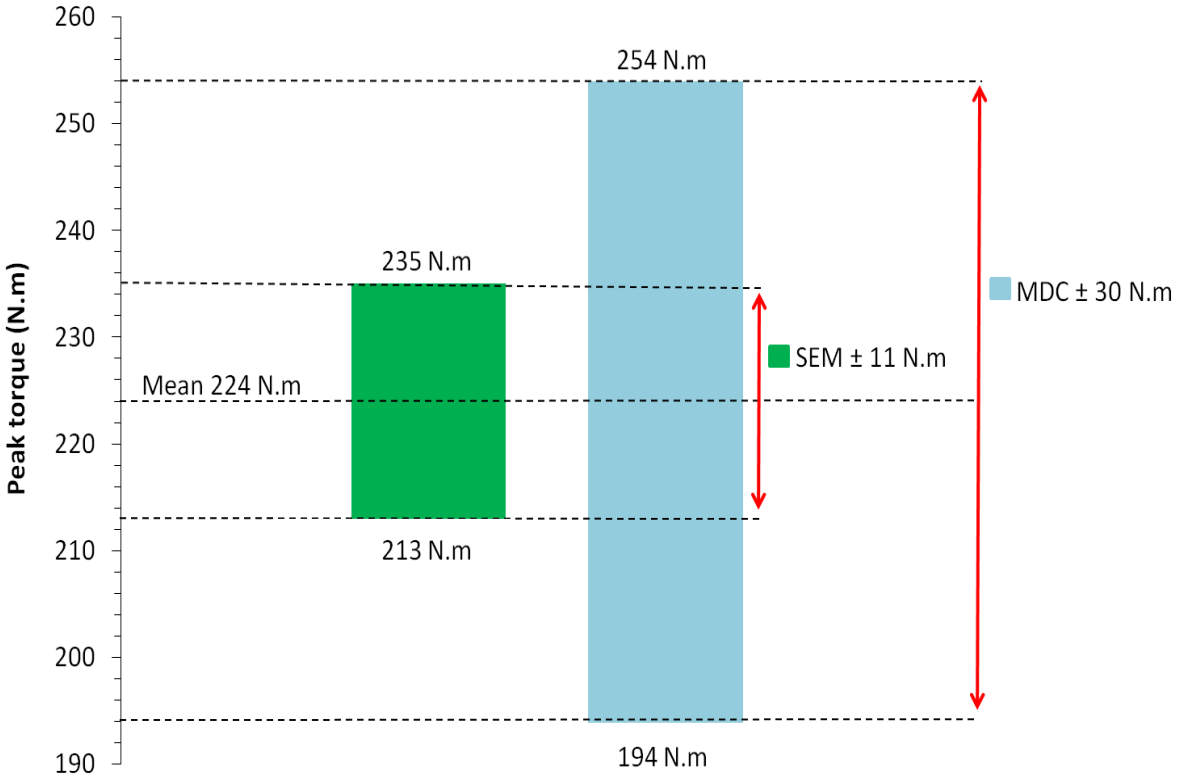


Figure 12. Example data of how to interpret Standard Error of Measurement (SEM) and Minimal Detectable Change (MDC)

The current study found that within in a session SEM of peak torque ranged between 10 and 15 N.m and its MDC ranged between 29 and 40 N.m for all conditions and the repetitions analysed. The current study also found that in a session SEM of angle of peak torque ranged between 3° and 4° and its MDC ranged between 9° and 10° for all conditions and the repetitions analysed. This means that if an individual was looking at changes or differences in their score from an acute intervention their score would have to at least to be above the SEM, and maybe above the MDC in order to observe real changes or improvements. In regards to real world changes of isokinetic torque, peak torque of the knee extensors at 60°/s has been reported to change up to 19 N.m after a bout of dynamic stretching of the knee extensors (Sekir et al., 2010). Angle of peak torque of the knee extensors tested isokinetically at 60°/s has been stated to change to up 16° towards the end range of knee flexion immediately after a prolonged eccentric stepping task (Bowers et al., 2004). Notably, these studies did not perform or cite any reliability studies of peak torque and angle of peak torque so the scores obtained may not

be above the measurement error of the test. Regardless, peak torque and angle of peak torque would be expected to be above the SEM and MDC reported in the current study based on the magnitude of change or difference from acute interventions and realistic changes from acute bouts of conditioning contractions such as during post-activation potentiation. Finally, it is important to note that the SEM and MDC for peak torque does depend on the number of repetitions performed during testing, since SEM and MDC increased with further repetitions performed in the current study.

5.4 Peak torque and its angle over 50 repetitions

5.4.1 Raw peak torque and its angle for repetitions one to fifty

No other study has explored or described peak torque and its angle over 50 grouped and interspersed repetitions of concentric knee extension at 60°/s. Figures 5 and 6 were presented to show the variation of peak torque and angle of peak torque produced by two participants over grouped and interspersed protocols. These figures highlight several observations of torque production, in which participants differed as to: (i) when they achieved their highest peak torque for all conditions, (ii) the maximum peak torque obtained for all conditions, and (iii) the angles at which peak torque was produced. Peak torque and its angle varied considerably from one repetition to another for participants P7 and P8. Despite these individual differences there are some consistent changes across participants such as the sudden increase in angle of peak torque for the interspersed protocol with a 60-s rest. Such fluctuations suggest that possible systematic changes may have occurred within the properties of the musculotendinous unit and the neuromuscular system. It is unlikely that participant motivation or pacing were the only factors that caused an increase of peak torque with repetitions as most participants did not achieve their maximum peak torque on the same repetition for each protocol.

5.4.2 Mean peak torque of 50 repetitions

The design of the current study allowed for the examination of whether performing more than the traditional two to six repetitions and a rest period between repetitions results in a higher magnitude of peak torque. Interspersed repetitions with a 60-s and 30-s rest had the highest mean peak torque for the first two and the first five repetitions and the highest mean peak torque over all 50 isokinetic concentric knee extension repetitions with 243 N.m (60-s) and 242 N.m (30-s). In contrast grouped repetitions had the lowest mean peak torque over all 50 repetitions of 231 N.m.

A difference in peak torque between different repetition protocols was also found by Stratford et al. (1990) who found that mean peak torque over five interspersed concentric knee extensions with a 30-s rest was 5% higher than five grouped repetitions at 60°/s. In the current study grouped repetitions resulted in more work completed over a shorter period of time, but this larger amount of work performed over a smaller timeframe resulted in more metabolic fatigue and a lower magnitude of peak torque. The rest period associated with interspersed repetitions not only may allow for a sufficient replenishment of phosphocreatine but it may also allow for muscle properties such as compliance and stiffness, elasticity, muscle temperature and neural mechanisms to stabilise and possibly optimise over time. Performing five grouped repetitions in accordance with contemporary isokinetic testing practice, arguably does not allow for the full optimisation of muscle properties and thus a lower magnitude of peak torque is achieved. Therefore if the goal of testing is to maximise peak torque, interspersed repetitions with either a 30-s or 60-s rest should be performed during isokinetic testing rather than grouped repetitions with a 120-s rest between sets.

5.4.3 Variability of the highest peak torque over repetitions

Traditionally within isokinetic testing protocols only two to six maximal repetitions are performed. This practice is supported by several authors (Baltzopoulos & Brodie, 1989;

Johnson & Siegal, 1978; Sawhill et al., 1982) who claim the highest peak torque is achieved within two to six grouped repetitions. This was not the case in the current study as the highest peak torque averaged across all 24 participants occurred at the 23rd, 27th and 22nd repetition for grouped repetitions, and interspersed repetitions with a 30-s and 60-s rest respectively. When compared with the maximum torque of the first five repetitions, the maximum torque of all 50 repetitions was 11%, 10% and 7% higher for grouped repetitions, and interspersed repetitions with a 30-s and 60-s rest respectively (see figure 7). These differences were shown to be statistically significant for all conditions, and the highest peak torque of all 50 knee extension repetitions was also shown to be reliably measured (table 8). The current study appears to be the first to consider maximal peak torque over multiple repetitions. The increase in peak torque with repeated maximal contractions suggests a possible augmentation of musculotendinous properties over time. Previous isokinetic reliability and testing studies have rarely explored beyond two to six repetitions and have not discussed the dynamic properties of skeletal muscle and the many factors that can affect torque production during maximal isokinetic repetitions.

5.4.4 Variability of angle at the highest peak torque over repetitions

The current study demonstrated that there was little or no change in the angle of the knee extensors at the highest peak torque between the first five repetitions and all 50 repetitions when averaged across participants. Previous studies investigating the acute changes of angle of peak torque (Bowers et al. 2004; Yeung & Yeung, 2008) after eccentric exercise have reported changes between 4°and 16° for the angle of peak torque of the knee extensors.

The type of movements and volume of contractions performed in these studies were very different to the multiple concentric isokinetic movements used in the current study. Although the changes in angle of peak torque after the eccentric exercise are in some cases large, the

reliability of measurements by Bowers et al. (2004) are not statistically described and it is not clear whether true changes in angle of peak torque were observed.

Yeung and Yeung (2008) do report a more robust preliminary test-retest reliability study of angle of peak torque. Their preliminary study measured angle of peak torque on two occasions and found that these measurements were within 1° of each other and that angle of peak torque had an ICC of 0.80. A slight problem with this preliminary test-retest reliability study is that Yeung and Yeung (2008) do not report the SEM of peak torque so any error associated with this measure is unknown.

Additionally, both of these studies used eccentric exercise and have not secured participants in the dynamometer using a specialised harness system. Thus the reported changes in angle of peak torque could have occurred due to the participants' movements in the chair creating discrepancies between the knee axis of rotation and the dynamometer axis of rotation. From the multiple repetitions and participant stabilisation practices used in the current study, it appears that the angle of the knee extensors at the highest peak torque alters minimally with repetitions.

5.4.5 Mean peak torque and its angle for repetitions one to fifty

The current study provides a rich description of peak torque and angle of peak torque over 50 grouped and interspersed repetition protocols (figure 9). Although peak torque and its angle do fluctuate within a given range there appears to be specific patterns observable across all repetition protocols. However, there are also clear individual differences of peak torque and angle of peak torque (figures 5 and 6), so this should be considered when interpreting the data of figure 9. While no physiological mechanisms were explored in this study, this section comments on possible reasons why peak torque and its angle may change over 50 repetitions.

As shown in the average group data of figure 9, the highest peak torque for the grouped protocol was typically achieved on the second or third repetition of every set of five repetitions.

As well as this the last repetition within each set usually generated the lowest peak torque. Due to the consecutive nature of grouped repetitions metabolic fatigue may likely accumulate within a set of five maximal repetitions. As a result torque production may decline within a set, which indicates a reduced availability of phosphocreatine (McMahon & Jenkins, 2002).

Not only was the highest peak torque for each set achieved on the second or third grouped repetition but the highest peak torque of each set did not decline substantially over the ten sets; in fact some participants achieved their highest peak torque between repetitions 41 and 50. Each maximal knee extension repetition lasted approximately 1.5-s and there was a 120-s rest between sets for the grouped repetition protocol. So the work to rest ratio of the grouped repetitions may not have allowed for sufficient replenishment of phosphocreatine stores for some participants. A sustained magnitude of peak torque over bouts of sets, even with the occurrence of metabolic fatigue could be due to certain physiological mechanism(s) such as an augmentation of musculotendinous properties or other muscular factors. However, what exactly causes a sustained magnitude of peak torque is unknown. It could be hypothesised that it is due to post-activation potentiation but it is difficult to differentiate this mechanism from changes in musculotendinous properties. In saying this, it could also be argued that phosphocreatine stores do not decrease significantly during isokinetic grouped repetitions as this type of exercise involves only one muscle group. Previous studies that have investigated the replenishment of phosphocreatine have done so with exercises such as sprinting or cycling which involve multiple muscle groups (Spencer et al., 2005). Regardless, future research is required to investigate the replenishment of phosphocreatine during isokinetic exercise and to explore the possible mechanisms responsible for the maintenance of maximum peak torque over sets of grouped repetitions.

Peak torque gradually increased for interspersed protocols with a 30-s and 60-s rest over the first 17 (30-s) and nine repetitions (60-s) (figure 9). An increase of peak torque with

repetitions could be suggested to be due to changes in the state of numerous properties of the neuromuscular system. Some possible factors that contribute to an increase of peak torque with repetitions are: (i) a decrease in the viscosity of skeletal muscle, (ii) increased motor unit recruitment, firing frequency and synchronisation (Cormie et al.,2011; Latash,. 1998), (iii) increased muscle temperature (Bergh & Ekblom, 1979), (iv) post-activation potentiation (Batista et al., 2007), (v) decreased inhibitory input from the CNS (Kandel et al., 1991), and (vi) decreased intrinsic stiffness (Magnusson, 1998). Many other factors can affect the increase in peak torque with repetitions. Those factors outlined above are only speculated to have a possible effect based on their suggested involvement during muscular contractions.

For interspersed repetitions with a 30-s rest there was a plateau in peak torque from repetition 18 onwards until an increase on the last repetition. The ability to sustain a high magnitude of peak torque over repetitions may indicate the stabilisation of various musculotendinous properties. It could be thought that the highest peak torque was only achieved on the last repetition due to improved motivation and concentration of the participant, or their ability to self pace, all of which may have allowed them to put in an extra effort. The highest peak torque achieved on the last repetition could have also been due to an augmentation of musculotendinous properties over time. Even though participant's ratings of perceived exertion were not recorded after each knee extension repetition, performing 50 repetitions would still have taken a lot of physical effort. So obtaining the highest peak torque after this number of repetitions is still unexpected even if some repetitions might have been at 95% of a participant's maximum effort. It is unlikely that motivation, self pacing and concentration were the only factors that enabled an increase of peak torque with repetitions, as not all participants achieved their highest peak torque over the last several repetitions. Additionally, those participants who achieved their highest peak torque later in the repetition count did not do this for all protocols. It could also be argued that an augmentation of musculotendinous properties and other muscular factors physiologically allowed participants to

achieve their highest peak torque on the last repetition. Regardless of the exact mechanism individuals still have the capability to produce maximum torque later than what would normally be expected.

Interspersed repetitions with a 60-s rest had a sudden rise in peak torque over the first nine repetitions, but after this peak torque gradually decreased before it rose over the last six repetitions. Prior to the experiment it was informally speculated that muscle temperature and peak torque would increase sharply over the first several repetitions interspersed with a 60-s rest. This was thought to occur due to the generation of heat in the contracting muscle, the temperature of blood coming into and through the leg, the increased rate of blood flow and the metabolism of the contracting musculature. It was also theorised that over repetitions muscle temperature and peak torque would eventually decline as there might be a net flux of heat away from the leg. The peak torque produced by some participants during the interspersed protocol with a 60-s rest was similar to that informally hypothesised. Other factors may also be responsible for an increase and gradual decline of peak torque such as muscle properties not being optimised or too much rest for the continuation of post-activation potentiation. Further research needs to confirm whether muscle temperature affects peak torque during interspersed repetitions with a 60-s rest as other factors could also affect torque production.

Interspersed repetitions with a 30-s rest may have allowed for a sufficient replenishment of phosphocreatine particularly for those participants who regularly performed repeated maximal muscular contractions. Interspersed repetitions with a 60-s rest would have certainly allowed for full or near full replenishment of phosphocreatine for most participants. So unlike grouped repetitions the peak torque achieved during interspersed repetitions particularly that with a 60-s rest may not be inhibited by a lack of phosphocreatine replenishment. The difference in the magnitude of peak torque attained between grouped and interspersed repetitions is primarily due to the rest associated with them, which consequently affects

movement history. However, the exact mechanism(s) that causes the difference in peak torque between interspersed and grouped repetitions is unknown. It could be speculated that since more phosphocreatine is available during interspersed repetitions a higher peak torque is attained. It could also be theorised that the rest between repetitions allows for an augmentation and optimisation of muscle properties and factors over time, thus a higher magnitude of peak torque is attained.

The exact contribution of different musculotendinous properties affecting peak torque and its angle attained over 50 repetitions for interspersed and grouped protocols is unknown, and further research is needed in this area. The behaviour of some musculotendinous properties such as stiffness or elasticity over multiple repetitions is also unknown. The musculotendinous properties responsible for force production interact in a complex manner especially over 50 interspersed and grouped knee extension repetitions. Some musculotendinous properties may optimise at different points in time, resulting in different magnitudes of torque with each repetition. Therefore it is the optimisation of different muscle properties that contributes to some of the observed variability peak torque and angle of peak torque over 50 grouped and interspersed repetitions during isokinetic knee extension.

The highest angle of peak torque for grouped repetitions occurred on the first repetition of every set of five repetitions (figure 9). As well as this the lowest angle of peak torque for grouped repetitions occurred on either the fourth or fifth repetition of every of set, except for the last two sets. The consecutive nature of grouped repetitions and the likely metabolic fatigue accumulated within a set of five maximal may affect angle of peak torque. Despite this speculation, the mechanisms that are responsible for the production of peak torque could be different to that of angle of peak torque. The exact contribution of these mechanisms affecting angle of peak torque are unknown and further research is required. Interestingly the highest peak torque of each set for grouped repetitions did not occur at the highest angle of peak torque

(closer to 90°), it occurred on average at 68°. Rather the first repetition of each set for grouped repetitions occurred at the highest angle of peak torque, which was on average at 70°. Therefore a higher angle of peak torque (closer to 90°) does not produce the highest peak torque.

The magnitude of changes of peak torque and its angle are far greater for grouped repetitions compared to interspersed repetitions within each set of five repetitions. Angle of peak torque for interspersed repetitions with a 30-s rest increased initially after the first three repetitions, which was the only protocol to do so, then decreased before fluctuating within a range of 70° - 72°. Large fluctuations of angle of peak torque could be indicative of changes in different musculotendinous properties. Peak torque and angle of peak torque for interspersed repetitions with a 30-s rest both start to stabilise from repetition seven and start to become more consistent within a given range. A rest between repetitions may allow muscle properties affecting peak torque and angle of peak torque to stabilise at the same time, but this of course is just speculation.

Angle of peak torque for interspersed repetitions with a 60-s rest initially decreased over the first four repetitions but from repetition 5 to 50 it gradually trended upwards. Peak torque and angle of peak torque for interspersed repetitions with a 60-s rest somewhat mirror each other. The decrease in angle of peak torque over the first four interspersed repetitions with a 60-s rest is paralleled by an increase in peak torque, and the downward trend of peak torque from repetition 10 is matched by an upward trend of its angle. As speculated above, a decline in muscle temperature may result in a decline of peak torque, so an increase of angle of peak torque may also be affected by such phenomenon. Mechanisms for acute changes in angle of peak torque over multiple isokinetic knee extension repetitions are unknown and further research of the mechanisms affecting angle of peak torque and its determinants are required.

The current study provides a model of the movement history of peak torque and angle of peak torque of the knee extensors over multiple interspersed and grouped repetitions. Such a model provides an insight into the complex behaviour of the musculotendinous unit and the neuromuscular system. Previous and current isokinetic strength testing and reliability studies would lead the reader to believe that torque production is a simple and constant process, but it is far more complex and integrated than that. Although peak torque and its angle are reliable they still fluctuate within a given range and are rarely ever exactly the same from one repetition to another. These fluctuations reflect the inherent biological variability of peak torque and its angle but also reveal certain systematic patterns. Peak torque, angle of peak torque and the torque-angle relationship are dynamic phenomena that are determined by a myriad of factors and musculotendinous properties. Given that peak torque and its angle vary from one muscular contraction to another, this suggests that the neuromuscular system somehow optimises torque production. The current study provides a platform for further research to investigate the musculotendinous properties and mechanisms responsible for peak torque and its angle, thus allowing for a better understanding of human muscular performance.

5.5 Repetitions at which the highest peak torque was obtained

5.5.1 Percentage of participants that obtained their highest peak torque over given repetition ranges

For the grouped repetitions 38% of participants achieved their highest peak torque between repetitions 11 – 20 (figure 10). This illustrates that the torque produced by some participants may have been affected by metabolic fatigue, possibly due to the consecutive nature of the grouped repetitions. However, 38% of participants also achieved their highest peak between repetitions 31 – 50 for the grouped protocol, which is not expected in a task requiring maximal muscular effort. This suggests a possible physiological mechanism

allowing participants to achieve their highest peak torque later in the repetition count during grouped repetitions.

One third of participants achieved their highest peak torque between repetitions 41 – 50 for interspersed repetitions with a 30-s rest, followed closely by 29% of participants between repetitions 11 – 20. As with grouped repetitions, there must be some mechanism(s) causing participants to obtain their highest peak torque later in the repetition count. Whether this mechanism(s) is the same as that which affects the grouped repetitions is unknown. Participant motivation is not the only factor causing participants to achieve their highest peak torque between repetitions 41 – 50 for interspersed repetitions with a 30-s rest. If this was the only factor then such a trend would be evident for all protocols, and participants would achieve their highest peak torque near the same repetition for each protocol.

Thirty eight percent of participants achieved their highest peak torque between repetitions 1 – 10 for the interspersed protocol with a 60-s rest, followed closely by 33% of participants achieving it between repetitions 21 – 30. This shows that peak torque reached a certain threshold early in the repetition count and this magnitude could be surpassed with further repetitions. The possible augmentation of muscle properties is not as evident with this repetition protocol, and the mechanism(s) underlying this magnitude threshold needs to be explored further.

5.5.2 Repetitions at which participants obtained their highest peak torque

Most participants varied as to which repetition they achieved their highest peak torque for grouped and interspersed protocols. Although the majority of participants differed in regards to the repetition at which they achieved their highest peak torque some participants were similar, which could have been coincidental. Variables of body mass, minutes of resistance training and sporting background all differed among these participants except for P9 and P28, whose sporting background and body mass were similar. As there was a lack of

consistency for these factors amongst these specified participants and that most participants did not achieve their highest peak torque at a similar repetition, it could be surmised that training history does may not always affect when individuals obtain their highest peak torque. If the training history of participants did have an effect, then possibly more evident patterns would be visible in figure 11. As such patterns were not visible this may indicate that other mechanism(s) are responsible for when participants achieved their highest peak torque.

5.6 Participant covariates

Participant's body mass was the only covariate that had significant effects upon mean peak torque of all 50 repetitions of concentric knee extension. Due to this effect, peak torque was expressed relative to body mass as a Standard Error of Measurement and Minimal Detectable Change (SEM peak torque (N.m) per kg and MDC peak torque (N.m) per kg). However, there was no or little difference between the relative SEM and MDC (peak torque (N.m) per kg) and absolute SEM and MDC values when expressed as a percentage of the group mean. Therefore expressing SEM and MDC of peak torque relative to body mass does not affect the reliability of peak torque.

5.7 Dichotomised peak torque data

Participants with a higher body mass had a lower SEM and MDC of peak torque for interspersed repetitions with a 30-s rest. Participants who were weaker had a lower SEM and MDC of peak torque for interspersed repetitions with a 60-s rest. Participants who performed more minutes of training had a lower SEM and MDC of peak torque for grouped repetitions. Therefore these are reasons why some participants are more reliable in the peak torque they produce compared to others depending on the condition. In the current study, when examining the reliability of peak torque over all 50 repetitions body mass, strength and minutes of training are factors to consider for interspersed repetitions with a 30-s rest, interspersed repetitions with a 60-s rest and grouped repetitions respectively. Future studies investigating the within-session

reliability of peak torque should consider that participants who are heavier for interspersed repetitions with a 30-s rest, weaker for interspersed repetitions with a 60-s rest and perform more minutes of training are most likely to produce a more reliable peak torque.

Chapter 6 - Conclusions

Results from the current study show that peak torque and angle of peak torque are reliable over the first five and all 50 repetitions of concentric knee extension tested isokinetically at 60°/s using either grouped and interspersed protocols. Only two repetitions of concentric knee extension tested isokinetically at 60°/s are required to obtain a reliable peak torque within a session, but for angle of peak torque at least five repetitions of isokinetic concentric knee extension at 60°/s are required to obtain a reliable measure.

Previous reliability studies of isokinetic knee extension have assumed that knee joint angle and dynamometer angle are the same. The preliminary work of the current study (see Appendix A) shows that the knee axis appears to move consistently from one knee extension repetition to another. As the knee axis appears to move consistently it is assumed that knee joint angle is also consistent, and that there is a consistent error between knee joint angle and dynamometer angle. As there might be a consistent error, and in the absence of a suitable alternative measure of knee joint angle, dynamometer angle can be used to consistently infer knee joint angle.

Interspersed repetitions with either a 60-s or 30-s rest obtained the highest mean peak torque for the first two, first five or all 50 isokinetic concentric knee extension repetitions. The total number of repetitions performed is also important for maximising peak torque as the maximum peak torque of all 50 repetitions was significantly higher compared to the maximum peak torque of the first five repetitions. So the type of repetition protocol selected and the number of repetitions performed both affect maximum peak torque.

The current study showed that little or no change occurred to the angle at the highest peak torque between the first five and all 50 repetitions. While previous studies have found that angle of peak torque does change significantly after eccentric exercise few have considered the SEM of angle of peak torque.

Average peak torque and angle of peak torque fluctuate within a given range over 50 grouped and interspersed repetitions of concentric knee extension tested isokinetically at 60°/s. Mean peak torque and its angle for the grouped protocol followed a cyclical pattern over each set of repetitions. For interspersed repetitions with a 30-s rest mean peak torque and its angle gradually plateaued over the 50 repetitions. Peak torque and its angle for interspersed repetitions with a 60-s rest followed a mirror image of each other over the 50 repetitions whereby peak torque gradually decreased and its angle trended upwards. Fluctuations of peak torque and angle of peak torque could be suggested to be due to changes in the state of numerous properties of the musculotendinous unit or other muscular factors. The increase of peak torque with repetitions for all conditions may possibly be due to an augmentation of muscle properties or other muscular factors over time, however, the exact mechanisms causing an increase of peak torque are unknown.

Individuals clearly differ as to when they achieve their highest peak torque for interspersed and grouped protocols, so more than the traditional five repetitions are necessary for most individuals. For most individuals the repetition at which they achieved their highest peak torque was different between interspersed repetitions with a 30-s and 60-s rest, and grouped repetitions. Although the majority of participants differed in regards to the repetition at which they achieved their highest peak torque some participants were similar.

Future studies investigating the within-session reliability of peak torque should consider that participants who are heavier for interspersed repetitions with a 30-s rest, weaker for interspersed repetitions with a 60-s rest and perform more minutes of training for grouped repetitions are most likely to produce a more reliable peak torque.

Chapter 7 - Study Limitations and Delimitations

Although these findings give valuable insight into the variability and reliability of isokinetic peak torque and angle of peak torque, several limitations and delimitations should be considered when interpreting the results of the current study.

7.1 Limitations

During testing of knee extension dynamometer angle from the Biodex System II isokinetic dynamometer was used to infer true knee joint angle as it is not actually measured by the dynamometer. True knee joint angle could not be measured in the current study due to the setup of the dynamometer and the isokinetic task (see Appendix A). Additionally, no other suitable instrument could measure true knee joint angle. True knee joint angle and dynamometer angle are not the same, as the knee axis and its angle moves differently during knee extension relative to the dynamometer axis and its angle. However, the movement of the knee axis during concentric knee extension appears to be consistent relative to the axis of the dynamometer from one repetition to another (see Appendix A). As the knee axis appears to move consistently from one repetition to another during concentric knee extension, it is assumed that knee joint angle is consistent, and that there is a consistent error between knee joint angle and dynamometer angle during isokinetic knee extension. As this consistent error may exist, dynamometer angle can therefore be used to infer measures of knee joint angle. However, the magnitude of this error or difference between knee joint angle and dynamometer angle is unknown.

The motivation levels of each participant would have varied during testing and their ratings of perceived exertion were not recorded after each maximal knee extension repetition. However, prior to testing participants were instructed to give their best maximal effort with each contraction at level 20 on a Borg rating of perceived exertion scale (6 no exertion at all, 20 maximal exertion). Each participant would have also had a different perception of what a maximal effort actually entails, so some participants may have applied more effort compared to

other participants. An increase of motivation and concentration towards the end of the repetitions and self pacing are all possible limitations. However, participants were given visual feedback of their torque production and their highest level of torque was used as their target for each repetition.

The design of the current study and its focus on the within-session reliability of peak torque and its angle is a limitation. The current study used a within-subject design to investigate the within-session reliability of peak torque and its angle across three different repetition protocols so the between-session reliability of these measures could not be outlined. Knowledge of the between-session reliability of peak torque and its angle has important implications for testing whether changes have occurred between sessions from interventions, as the error associated with such measures can be reported and considered. This not to say that between-session reliability is more important rather interventions between sessions are more common than those within a session.

The Standard Error of Measurement (SEM) itself has some limitations. Firstly, the SEM is only an estimate of the within-subject standard deviation and it covers about 68% of the variability of a measure (Portney & Watkins, 2002). For example, if mean peak torque is 220 N.m and the SEM of peak torque is 10 N.m, this means that there is approximately a 68% chance that an individual's true score falls within ± 10 N.m, or between 210 N.m and 230 N.m. There are at least four different calculations for SEM (Stratford, 2004), and the current study used one of the more common calculations within reliability studies of isokinetic knee extension.

The days between test sessions were not the same for some participants due to limited availability of the laboratory and participant time. Participants were also not tested at exactly the same time each day for the same reasons mentioned above. These factors may have caused variation in torque production from one testing session to another.

Some participants performed high intensity exercise between testing sessions even though they were asked not to do so. Such exercise between testing sessions may have slightly affected their torque production.

The total minutes of endurance training performed by participants each week on average over the previous six months was not recorded. Such information would have provided more information on the training characteristics of each participant.

Participant sleep patterns prior to testing and diet were beyond the control of the experiment. Participants were asked to keep these factors consistent between test sessions and abide by test preparation guidelines.

7.2 Delimitations

The following were some delimitations of the current study that may impact on the generalisability of the results:

(i) The study examined concentric knee extensor strength, which is a single joint movement involving the knee extensor muscles.

(ii) The study used the angular velocity of 60°/s during isokinetic knee extension.

(iii) Only physically active or trained male participants with an average age of 22.7 ± 3.1 y (18.5 – 29.3 age range) participated in this study.

Chapter 8 - Implications and Future Directions

Interspersed and grouped repetitions both had similar levels of reliability for peak torque and angle of peak torque of the knee extensors over the first five and all 50 repetitions. If practitioners simply require a reliable protocol to test peak torque and angle of peak torque then either interspersed or grouped repetitions can be used. However, if the goal of testing is to achieve the highest peak torque possible then interspersed repetitions should be used.

Traditionally isokinetic testing of the knee extensors consists of 2 – 6 grouped repetitions, but as the current study has shown some participants obtain their highest peak torque after 20 repetitions. So a testing protocol should consider such an increase of peak torque with repetitions. A protocol could consist of one angular velocity such as 60°/s, and a maximum of 20 interspersed repetitions with a 30-s rest in order to achieve a score close to an individual's maximum peak torque. Future studies could investigate the repetition at which maximum peak torque occurs at using different isokinetic velocities over multiple grouped and interspersed protocols, as different velocities are commonly used in practice.

As the current study was limited to within-session reliability future research should focus on the between-session reliability of peak torque and angle of peak torque. Future research of between-session reliability should also use interspersed repetitions with either a 30-s or 60-s rest over multiple repetitions. This would then provide evidence as to whether angle of peak torque can be reliably tested from one session to another, allowing it to be used as a measure in short or long term intervention studies. Thus the true significance of angle of peak torque could be explored if it was deemed reliable between sessions.

If practitioners or testers are examining the magnitude of change of peak torque or angle of peak torque within a session such as from acute interventions or comparing the differences in strength between limbs then scores need to reflect true changes. The current study found a Minimal Detectable Change (MDC) of peak torque between 29 – 40 N.m for all protocols over the first five and all 50 repetitions. The MDC of angle of peak torque was between 9° – 12° for

all protocols over the first five and all 50 repetitions respectively in the current study. As discussed previously the reported MDC of the current study does seem quite high relative to the Standard Error of Measurement (SEM) particularly for peak torque. MDC values found in the current study should be taken into account and are a guideline in order to realistically detect true changes within a session. The reliability of peak torque and angle of peak torque of the knee extensors outlined in the current study will allow individuals to assess true changes from acute interventions within a session.

Future within and between-session reliability studies of isokinetic peak torque and angle of peak torque need to investigate the within-subject variation of these measures. Previous isokinetic reliability studies focus primarily on Intraclass Correlation Coefficients (ICCs) particularly for angle of peak torque. ICCs do not provide information on the magnitude of error for a measure within an individual, rather it examines between-subject variability (Atkinson, 2003). Forms of within-subject variation such as SEM and Coefficient of Variation outline how much error there is within a measure for individuals. Knowledge of how much error is associated with a measure is important in quantifying how much of a change has actually occurred and whether such changes are true. Therefore, within-subject variation enables accurate tracking of changes in a measure for an individual. If future reliability studies examine the within-subject variation of angle of peak torque such information is meaningful to acute or chronic studies using this measure.

Studies that measured changes in angle of peak torque (Brockett et al., 2001; Bowers et al., 2004: Koller et al., 2008; Brughelli et al., 2010b) had insufficient evidence for its reliability. These studies did not consider the SEM and MDC of angle of peak torque. If studies are going to state changes in the magnitude of a measure after an intervention, they should at least consider the error of the measure. If future studies do this, readers will not only

know the SEM of a given measure, but also whether the magnitude of change is above the threshold of error.

The current study found systematic patterns of peak torque and its angle over 50 grouped and interspersed repetitions of concentric knee extension tested isokinetically at 60°/s. The exact mechanisms contributing to torque production during interspersed and grouped repetitions is unknown, and further research is required such as measuring muscle temperature or taking muscle biopsies. Knowledge of the mechanisms that primarily contribute to peak torque and its angle during isokinetic knee extension will create a platform for further studies to examine and manipulate such measures in order to improve muscular performance. Knowledge of the mechanisms of torque production will also provide a timeframe of when certain mechanisms optimise and stabilise. The current study opens up a whole new area of torque production research. Specifically, it will allow for future research to investigate how individuals produce certain levels of torque and whether muscular performance can be improved. Research examining the mechanims of acute torque production should not be limited to strength testing or training, other sports such as sprinting could be benefittedfrom such research.

The current study investigated the within-session reliability of peak torque and angle of peak of the knee extensors with participants who were physically active or trained. Future studies describing the within-session reliability of peak torque and angle of peak torque over multiple repetitions should do so with resistance and endurance trained individuals, or individuals from different sports such as sprinting or road cycling. Examining different groups of individuals may give an insight into some mechanisms responsible for torque production. In addition, different movements such as knee flexion, different angular velocities and types of muscular contractions (e.g. eccentric) could also be investigated using a similar study design.

As torque production is maximised within a session by having a rest between repetitions, this same method of prescription could be used for resistance training or other forms of training to improve an individual's strength. If an individual used a rest between repetitions during resistance training this may lead to chronic adaptations in the musculotendinous unit and greater increases in strength over time compared to using a rest between sets. Such a training method may have implications for strength training, weight lifting or other sports such as sprinting. Future research could investigate whether using a rest between repetitions leads to greater increases in strength over time compared to the traditional model of a rest between sets.

Future research could also endeavour to measure true knee joint angle rather than being reliant on dynamometer angle to infer true knee joint angle. The preliminary work of the current study has experimented with various methods to measure true knee joint angle, such as biomechanical analysis of the knee joint (ankle, knee and hip axes) and use of electro-goniometers over the knee joint. However, both methods did not provide accurate information. Another way to measure true knee joint angle would be the use of a portable biomechanical analysis system such as Vicon (Vicon, Denver, USA), but such analysis would be time consuming. Whether true knee joint angle can actually be measured whilst individuals perform isokinetic movements is unknown, however some researchers may want to know what true knee joint angle is during isokinetic movements. Future isokinetic research should use a specialised harness to secure participants in the dynamometer chair like that used in the current study. Using this harness minimises extraneous hip and knee axis movements during knee extension. Minimising such movements may improve the reliability of angle of peak torque.

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Appendices

Appendix A: Preliminary study

Appendix B: Biodex System II isokinetic dynamometer

Appendix C: Visual Analogue Scale – muscle soreness

Appendix D: Specialised harness system

Appendix A: Preliminary study

Consistency of the knee axis of rotation during concentric actions of isokinetic knee extension

Isokinetic dynamometry is used to assess and monitor muscular strength. It involves the measurement of a muscular action against a motor controlled exercise machine, with the movement performed at a constant angular velocity (Baltzopoulos & Brodie, 1989). During isokinetic dynamometry an individual's joint axis of rotation is aligned with the axis of rotation of the dynamometer. Measurements of muscular torque and dynamometer angle are obtained during testing as an individual applies force to the lever arm and moves their limb through a given range of motion. Dynamometer angle is used to infer joint angle during different movements, allowing for specific measures such as angle of peak torque and angle specific torque.

When dynamometer angle is used to infer the measurement of different joint angles there is an assumption that the movement of certain joint angles and their axes of rotation are the same as the movement of the dynamometer angle and its axis of rotation. However, actual true joint angle is not measured by the isokinetic dynamometer. For example, during isokinetic knee extension the lever arm of the dynamometer moves around one axis point, whereas the axis of the knee moves through many points during knee extension (Smidt, 1973). As well as this there is a difference between the arc of the dynamometer angle versus the arc of true knee angle. Therefore, the initial alignment of the knee axis with the dynamometer axis is not maintained during isokinetic knee extension. These aspects are ultimately problematic when dynamometer angle is used to infer true knee joint angle as there is a difference or error between dynamometer angle and true knee joint angle during isokinetic knee extension. This difference or error obscures the measurement of true knee joint angle and thus the validity of specific measures such as angle of peak torque and angle specific torque during isokinetic knee extension.

Only one study in all of the reliability studies investigating angle of peak torque during isokinetic knee extension (Ayala et al., 2012) acknowledges that dynamometer angle is different from true knee joint angle, and that this difference results in an error associated with dynamometer angle. Only a few studies have practically considered or investigated the difference between dynamometer angle and true knee joint angle during isokinetic knee extension, and whether inferring true knee joint angle from dynamometer angle is a valid measurement (Reimann, Verdonck & Wiek, 1997; Sorensen, Zacho, Simonsen, Dyhre-Poulsen & Klausen, 1998; Verdonck, Reimann & Wiek, 1997). All current and previous isokinetic reliability studies of knee extensor angle of peak torque have ignored such literature and have not critically examined what they are measuring when they are using dynamometer angle.

Although there is a difference between dynamometer angle and true knee joint angle during isokinetic knee extension, it is unknown how consistent this difference is. In order to determine whether true knee joint angle is consistent from one repetition to another and thus whether there might be a consistent difference between it and dynamometer angle, the movement of the knee axis during knee extension was measured in the current preliminary study. Currently, it is unknown how consistent the knee axis moves from one repetition to another during maximal concentric actions of isokinetic knee extension. If the knee axis moves consistently from one repetition to another during concentric actions of isokinetic knee extension then it can be assumed that there is a consistent difference between dynamometer angle and true knee angle. This can be assumed as the movement of the ankle joint during knee extension is limited as it is strapped onto the dynamometer lever arm. As well as this the hip joint during knee extension has a limited range of movement and may move consistently if the knee axis does. Therefore, it is assumed if the knee axis moves consistently from one repetition to another during isokinetic knee extension so will the hip and ankle joints, and consequently movements of knee joint angle may also be consistent. Due to this, the error associated with dynamometer angle when it is used to infer true knee joint angle would then at

least be a consistent error. Although the values of dynamometer angle are different from the values of true knee joint angle during isokinetic knee extension, a consistent error means that the difference between the two values will approximately always be the same during the knee extension movement.

The purpose of this study was to describe the consistency of the movement of the knee axis from one repetition to another during concentric actions of isokinetic knee extension relative to the dynamometer axis. If the knee axis does move consistently from one repetition to another then there might be a consistent difference between dynamometer angle and true knee joint angle. Determining the consistency of the knee axis from one repetition to another relative to the dynamometer axis will inform whether dynamometer angle can be used to measure true knee joint angle during concentric knee extension.

Methods:

Participants:

Four physically active participants (1 male, 3 females) were recruited from the School of Physical Education at the University of Otago. Participants had no history of neuromuscular problems or musculoskeletal injuries of the lower limb. Prior to the study, each participant was provided with a full explanation of the nature and purpose of the research. Each participant completed an informed consent and a pre activity questionnaire prior to participation in the study. Participants were instructed not to perform any vigorous or intense physical activity within 24 hours prior to the testing session. These participants did not partake in the primary study of this thesis.

Equipment and video analysis setup:

A Biodex System II isokinetic dynamometer (Biodex Corporation, Shirley, NY) was employed during testing with Chart 7 Pro version 7.0.1 software (ADInstruments, NZ) used to record torque, velocity and angle from the dynamometer. Other models of the Biodex isokinetic dynamometer have been shown to be reliable in measuring torque, velocity and angle within and between days (Drouin et al., 2004; Taylor et al., 1991). The sampling frequency of the Chart 7 software was set at 1000Hz. A powerlab 8/30 (ADInstruments, NZ) was used to transfer the data from the Biodex isokinetic dynamometer to the Chart software programme. The sagittal plane movement of knee extension was recorded with a Panasonic SDR-H101 video camera (Panasonic Corporation, Osaka, Japan) at 50Hz and 25 frames per second. The camera was placed 5.8 m away from the isokinetic dynamometer on a tripod at a height of 82 cm directly square to and in line with the axis of the dynamometer. A laser (power output 50 mw and wavelength 532 nm) was mounted on a tripod also at a height of 83 cm adjacent to the left of the camera, and was also directly aligned with the axis of the dynamometer. The laser was used as a reference point for the dynamometer axis during filming. A spotlight was positioned adjacent to the right of the camera. A timing light was positioned near the isokinetic dynamometer and connected to the powerlab 8/30. The timing light allowed for a synchronisation of data between the Chart 7 software and the video camera.

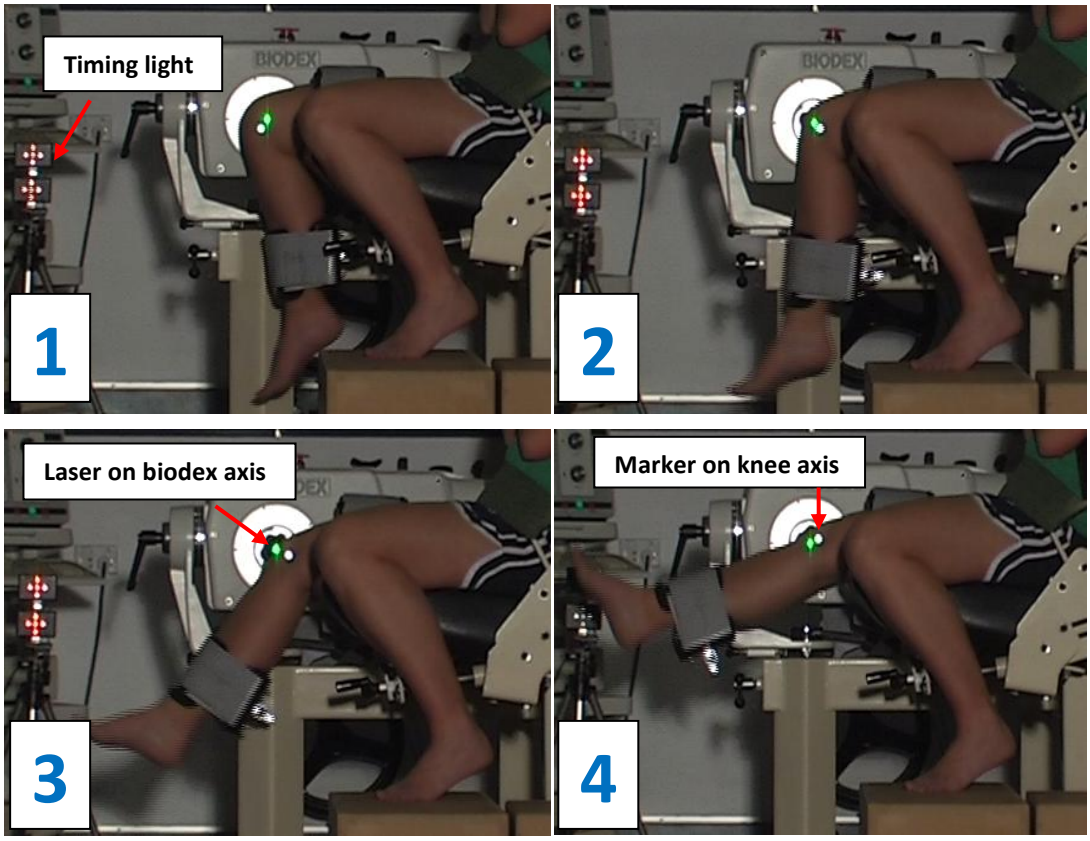


Figure 1. Example of a participant's knee axis movement during isokinetic knee extension from their starting range to motion towards their end range of motion

Procedures:

Prior to data collection, calibration of the video camera was completed using a 1.2 m x 1.2 m board which was placed directly against the axis of the dynamometer. Preceding the commencement of testing calibration checks of position and torque were taken from the Biodex isokinetic dynamometer and analysed on the Chart software. The Biodex isokinetic dynamometer setup consisted of a soft cushioning, medium sensitivity and the percentage range dials were set at 100%.

Prior to testing the height and body mass of participants was obtained with each participant completing one testing session. A biomechanical marker was placed on the medial epicondyle of the right knee with double sided tape. Participants were positioned in the Biodex isokinetic dynamometer, with the biomechanical marker on the right knee axis (medial epicondyle) aligned as closely as possible to the laser pointing at the dynamometer axis. The

participants' knee axes were aligned as closely as possible to the dynamometer axis as the seat could only be moved back a certain distance and could not be moved up or down. The participants left leg was positioned just to the side of the dynamometer seat so it did not obscure the video recording of the right knee axis. The leg was placed on a box to ensure participants were comfortable, and participants were asked not to apply any force to the box during repetitions.

The participants' right leg was secured firmly with an ankle strap positioned superior to the medial malleolus. Straps also secured the thigh and the waist, and shoulder straps were secured diagonally across the torso to the opposite hip. Knee range of motion was set from 105° to the participants end range of knee extension. The velocity of the Biodex isokinetic dynamometer was set at 60°/s for the knee extension phase. Thorough instructions and details of how to perform the knee extension tasks was outlined to participants, however no verbal encouragement was given to the participants during testing. Visual feedback of torque from each repetition was displayed during testing, with the participant's highest level of torque achieved used as their acquired target for each repetition.

Prior to testing participants were instructed to do their best and to push as hard as they can during knee extension like they are kicking a ball, and slowly lower the leg during the knee flexion phase. A Borg rating of perceived exertion scale from 6 – 20 (6 no exertion at all, 20 maximal exterion) was explained to the participants. Each participant was asked to perform each contraction at level 20 on the scale.

Once the participants were strapped into the chair they performed 50 maximal concentric knee extension movements with their right limb. Each repetition was interspersed with a 30-s rest period. At the conclusion of each testing session participants were given a 5 min warm down on a Monark ergomedic 828E stationary bike (2 kp at 75 rpm) and completed a standing quadricep stretch for four sets of 30-s.

Data acquisition and analysis:

Measures obtained during testing included dynamometer angle and the movement of the knee axis during each isokinetic knee extension movement. Motion capture data of the knee axis was digitised and analysed in Simi Motion 3D software version 7.2 (Simi Reality Motion Systems, GmbH, Germany). The X and Y co-ordinates of the knee axis were digitised for all 50 isokinetic knee extension repetitions.

Results:

Four physically active individuals (1 male, 3 females) completed testing. The mean age, body mass and height ± SD for the participants was 24.7 ± 2.7 years, 75.6 ± 12.5 kg and 172 ± 10.2 cm respectively. As shown in figure 2, the knee axis of participant one during repetitions 1, 10, 20, 30, 40 and 50 of concentric knee extension moved horizontally downward to the right during the first phase of knee extension. As the knee continued to extend its axis moved upwards diagonally till the end of the movement.

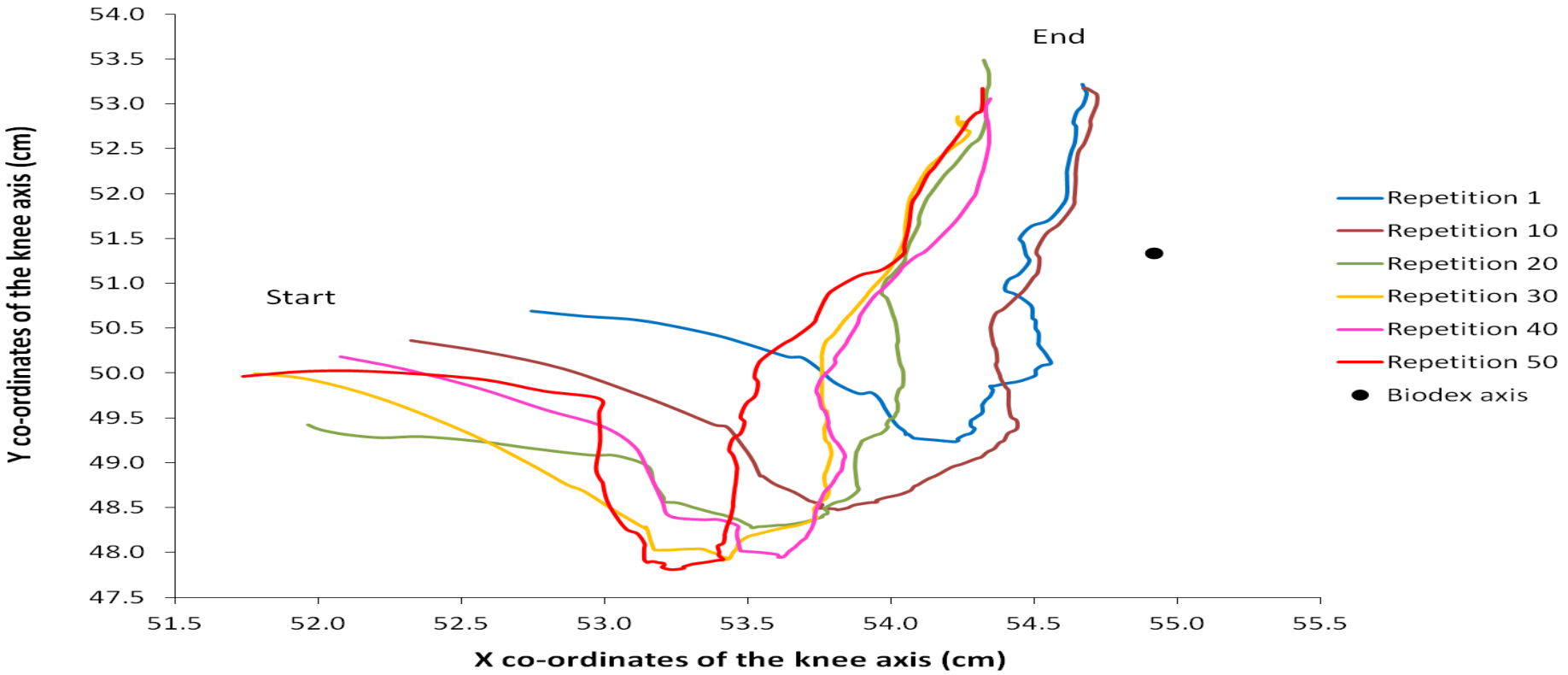


Figure 2. Movement of the knee axis for participant one during repetitions 1, 10, 20, 30, 40 and 50 of concentric knee extension tested isokinetically at 60˚/s

As shown in figure 3, the movement of the knee axis for participant one follows a similar pattern over 50 isokinetic knee extension repetitions. However, the knee axis did drift downwards to the left over 50 repetitions. The knee axis moved up to 3.2 cm horizontally and 6.2 cm vertically during the knee extension movements.

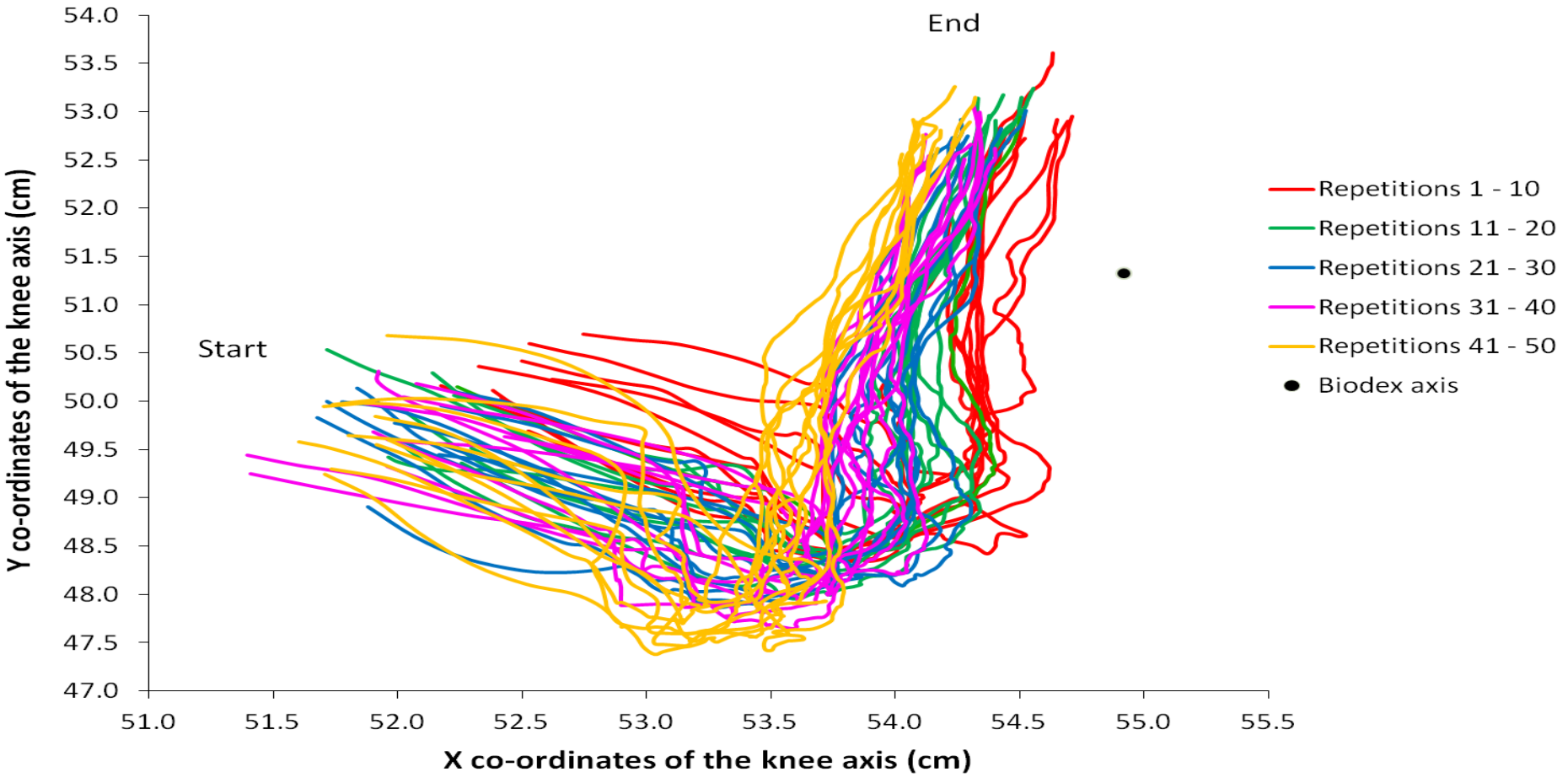


Figure 3. Movement of the knee axis for participant one during 50 repetitions of concentric knee extension tested isokinetically at 60°/s

As shown in figure 4, the knee axis of participant two during the first phase of isokinetic knee extension moved horizontally to the right before it moved slightly downwards. As the knee continued to extend its axis moved directly upward till the end range of motion.

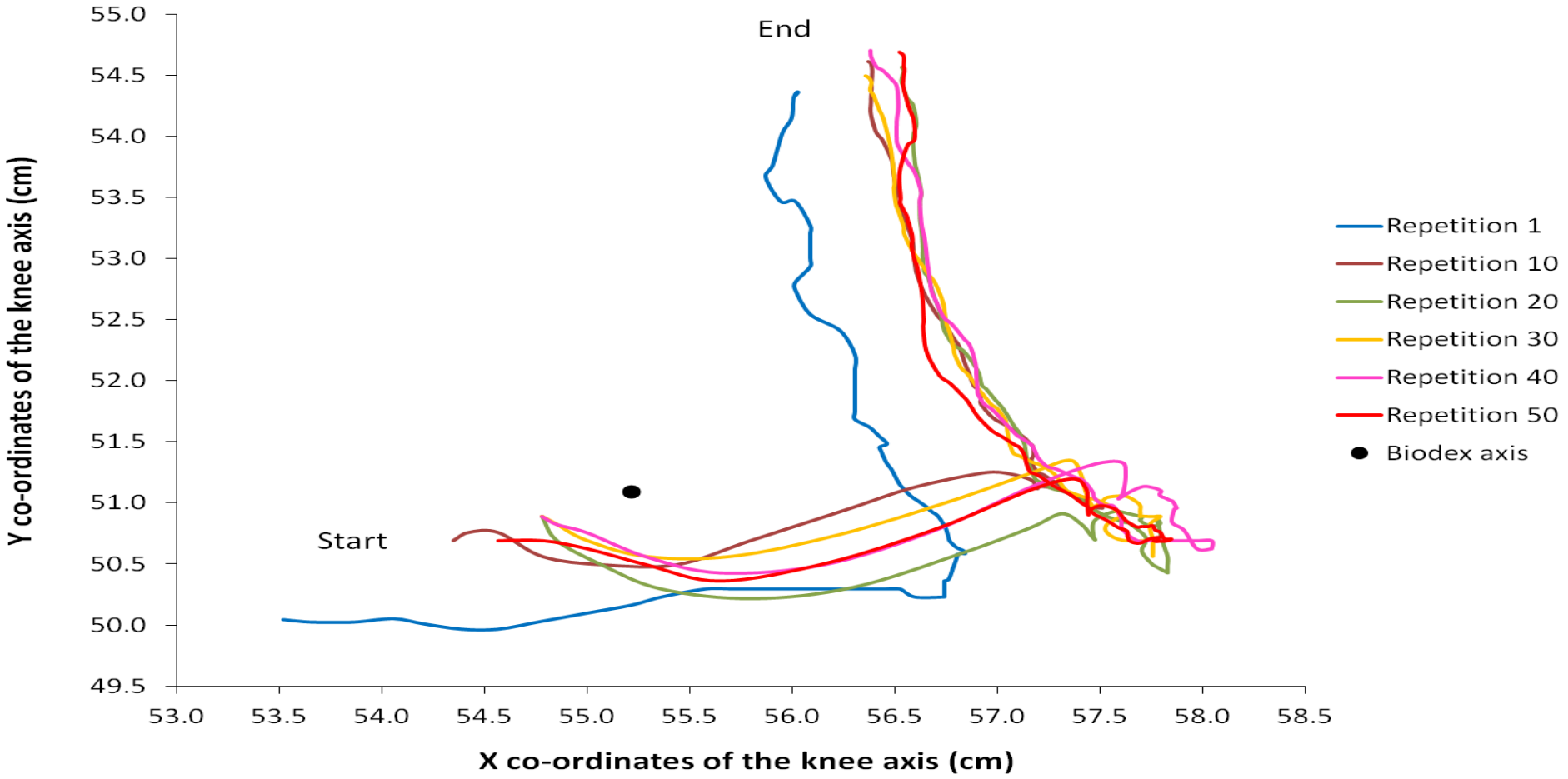


Figure 4. Movement of the knee axis for participant two during repetitions 1, 10, 20, 30, 40 and 50 of concentric knee extension tested isokinetically at 60˚/s

As shown in figure 5, the knee axis for participant two moved similarly over 50 isokinetic knee extension repetitions, although the knee axis did slightly drift to the right over 50 repetitions. The knee axis moved up to 4.7 cm horizontally and 5 cm vertically during the knee extension movements.

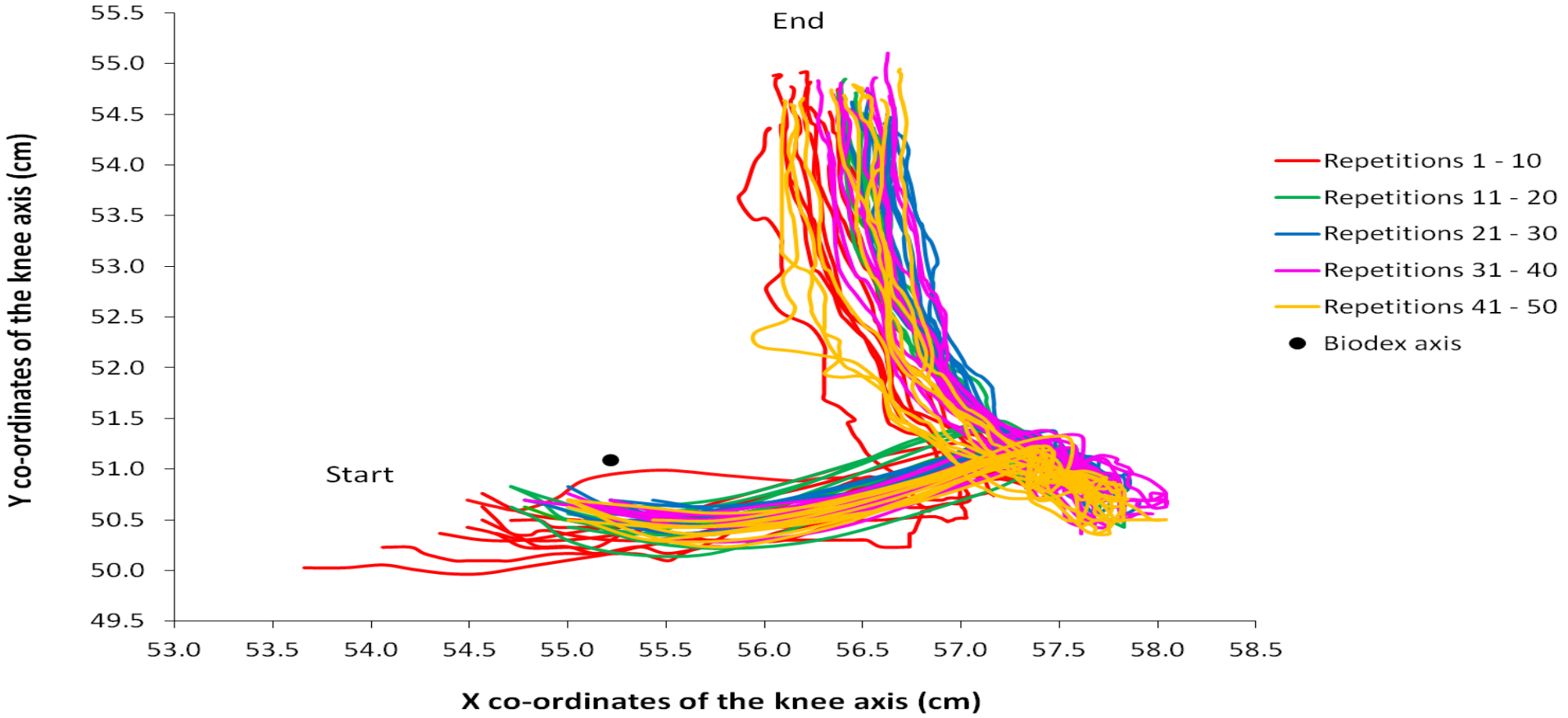


Figure 5. Movement of the knee axis for participant two during 50 repetitions of concentric knee extension tested isokinetically at 60˚/s

As shown in figure 6, the knee axis of participant three during the first phase of isokinetic knee extension moved horizontally to the right then it moved downwards. As the knee continues to extend its axis moved in an upward direction.

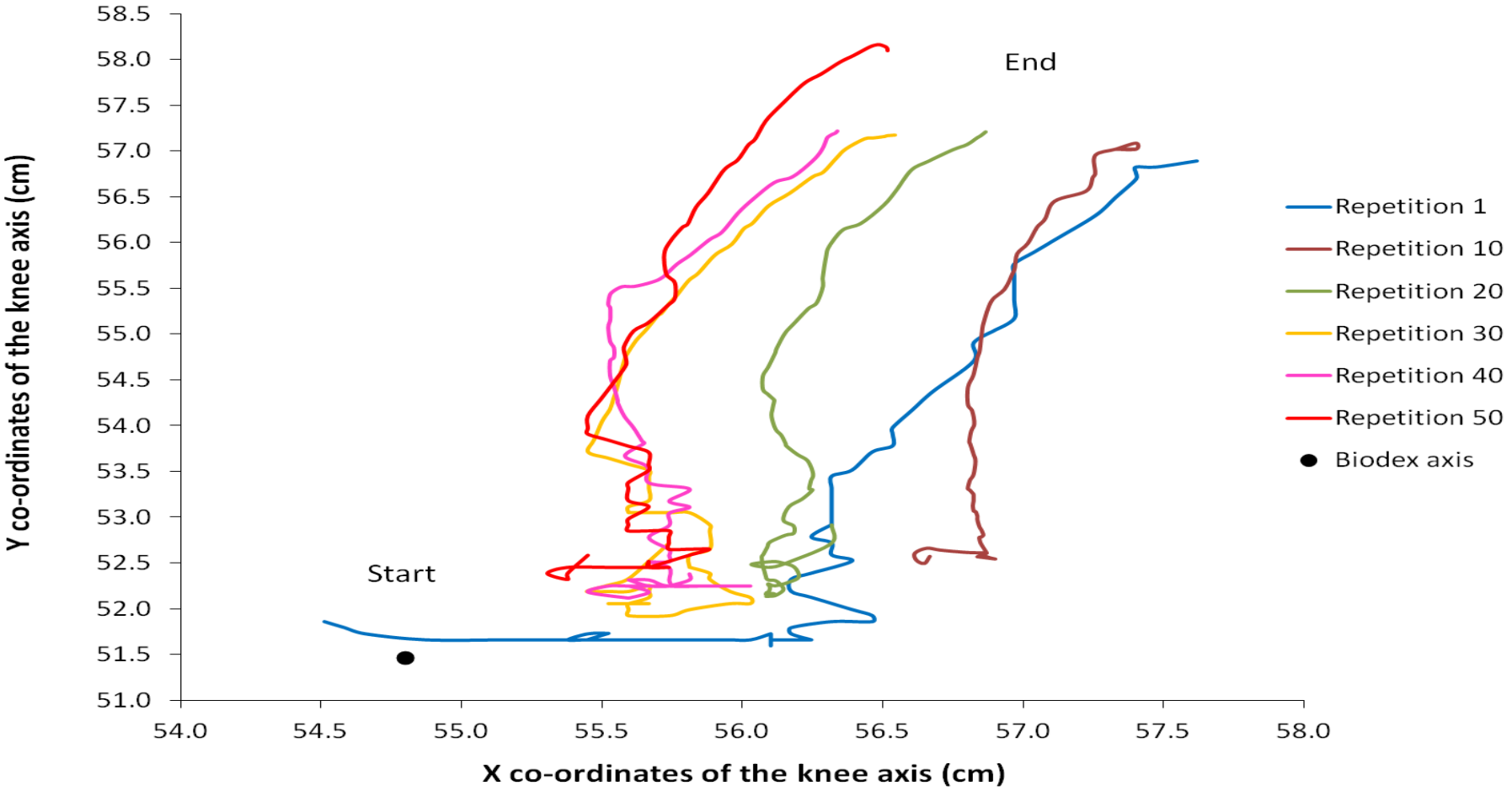


Figure 6. Movement of the knee axis for participant three during repetitions 1, 10, 20, 30, 40 and 50 of concentric knee extension tested isokinetically at 60˚/s

As shown in figure 7, the knee axis for participant three follows a similar distribution over 50 isokinetic knee extension repetitions, although the knee axis did slightly drift to the left over 50 repetitions. The knee axis moved up to 3 cm horizontally and 7 cm vertically during the knee extension movements.

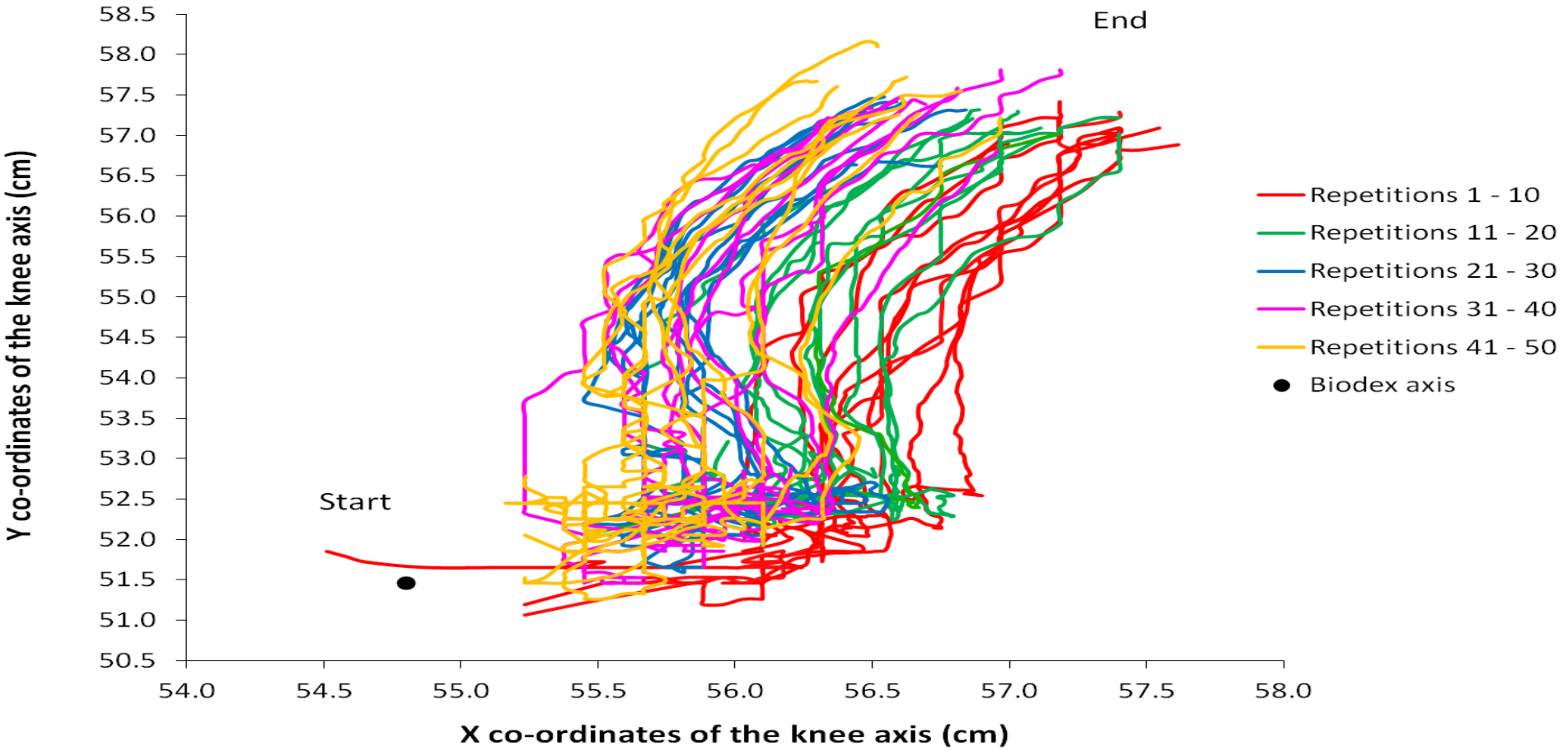


Figure 7. Movement of the knee axis for participant three during 50 repetitions of concentric knee extension tested isokinetically at 60°/s

As shown in figure 8, the knee axis of participant four during the initial phase of isokinetic knee extension moved horizontally to the right then it looped downwards. As the knee continued to extend its axis moved upward in an exponential manner.

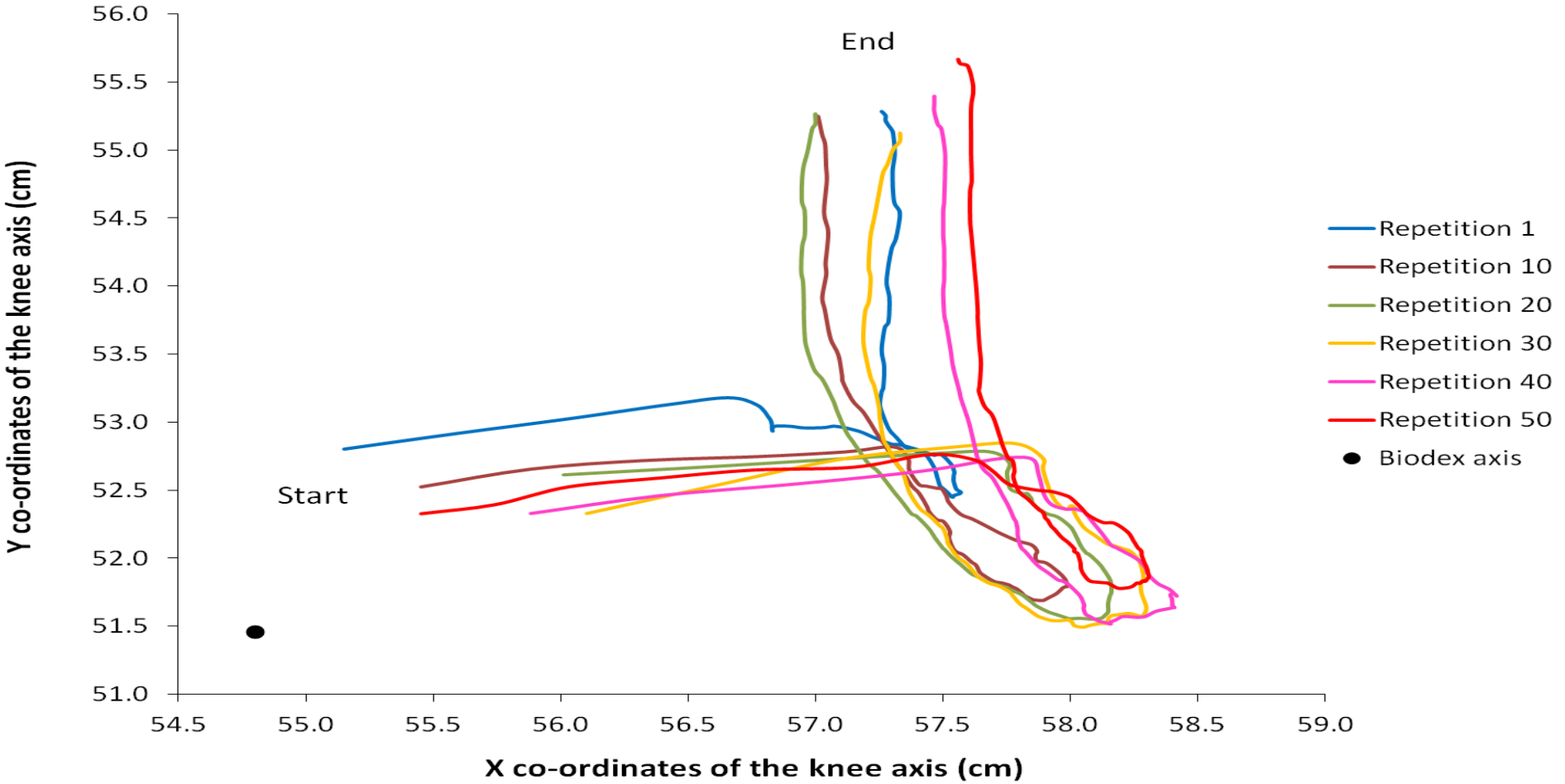


Figure 8. Movement of the knee axis for participant four during repetitions 1, 10, 20, 30, 40 and 50 of concentric knee extension tested isokinetically at 60˚/s

As shown in figure 9, the knee axis for participant four follows a tight trend over 50 isokinetic knee extension repetitions, although the knee axis did slightly drift to the right over 50 repetitions. The knee axis moved up to 3.2 cm horizontally and 4.1 cm vertically during the knee extension movements.

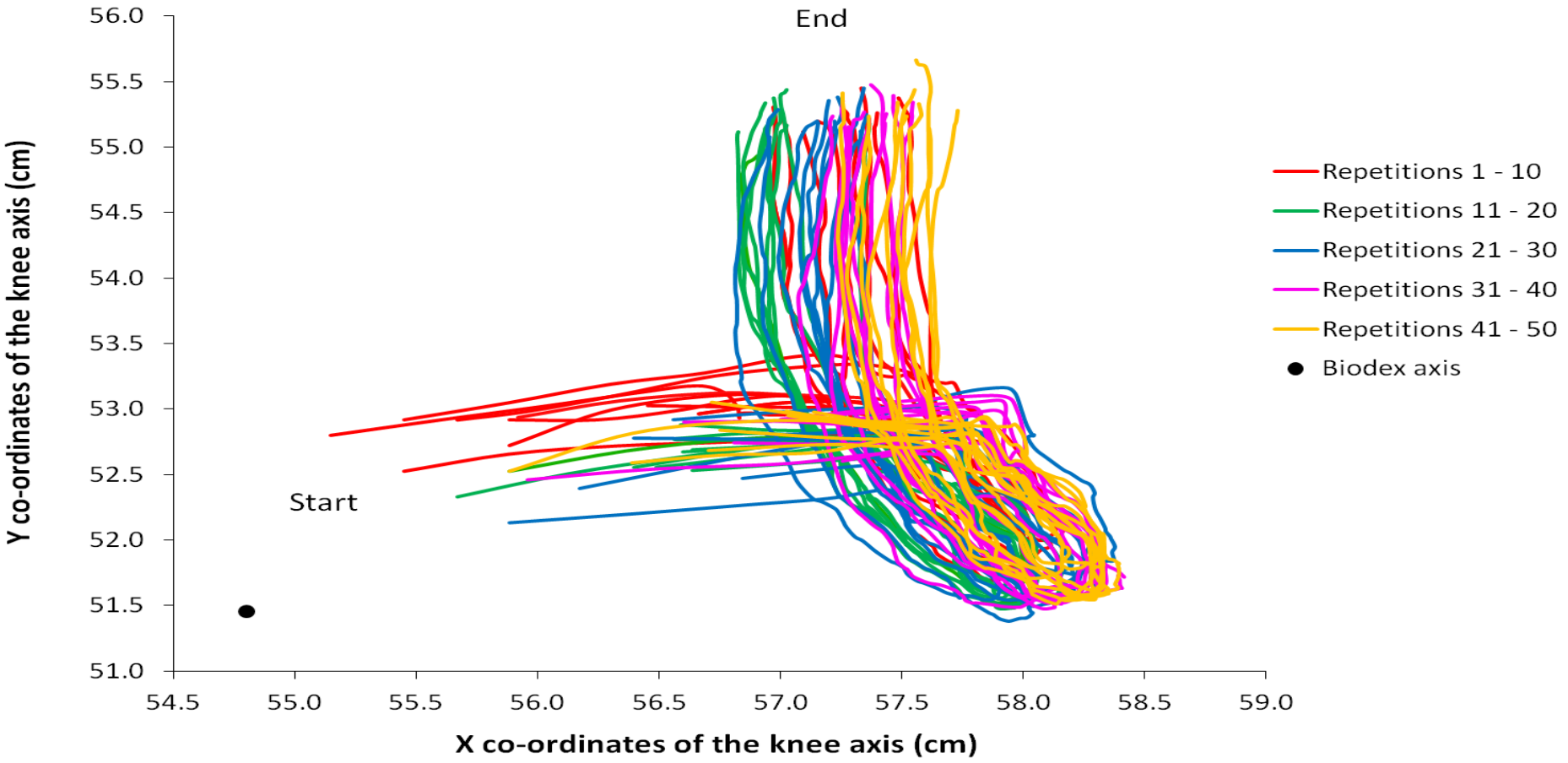


Figure 9. Movement of the knee axis for participant four during 50 repetitions of concentric knee extension tested isokinetically at 60˚/s

Discussion:

The purpose of this study was to determine the consistency of the movement of the knee axis during concentric actions of isokinetic knee extension from one repetition to another relative to the dynamometer axis. The results of this study showed that the knee axis did have a similar pattern and appeared to move consistently for each individual participant over 50 knee extension repetitions, as shown in figures 3, 5, 7 and 9. The participants knee axis of rotation moved approximately within a range of 3.2 – 4.7 cm horizontally and 4.1 – 7 cm vertically during knee extension from 105° to end range of motion. The movement of the knee axis did drift within these reported ranges for each participant over the 50 repetitions, however how much of an effect this has on dynamometer angle is unknown. The knee axis during isokinetic knee extension moved very differently between participants and is no doubt due to the individual differences in limb length, musculature of the right leg and the magnitude of torque developed (Sorensen et al., 1998). The knee axis for all participants moved initially within the horizontal plane then rose sharply within the vertical plane. Although the dynamometer lever arm moves around one axis point, its axis will move slightly during isokinetic knee extension due to the large amount of force generated.

The results of this kinematic study provide further clear evidence that the knee axis moves differently compared to the dynamometer axis during isokinetic knee extension, and because of this true knee joint angle is obviously different from dynamometer angle. The knee axis moves throughout isokinetic knee extension due to the compression of the seat, deformation of musculature and tissue at the back of the thigh, and the elevation and depression of the hips during knee extension. The anatomical structure of the trocho-ginglymus knee joint also causes its axis to move throughout knee extension. As the knee extends, the femur rolls and glides over the menisci, with the femur medially rotating towards the end range of extension all of which cause its axis to move upward and forward in a semicircular motion. Smidt (1973) found that the axis of rotation of the knee displaced 3.2 cm

through a 90° range during knee extension. As more force is applied to the lever arm during isokinetic knee extension, the tissue and musculature at the back of the thigh are compressed further, resulting in a greater movement of the knee axis (Sorensen et al., 1998). This would account for some of movement variation of the knee axis with each repetition.

The difference between knee joint angle and dynamometer angle was investigated by Sorensen et al. (1998). They used an electro-goniometer over the lateral aspect of the knee joint to measure true knee joint angle and compared this measurement to dynamometer angle during isokinetic knee extension at 60°/s. They found that goniometer angle (knee joint angle) was much larger than dynamometer angle during knee extension, with differences ranging between 13° and 33°. However, the reliability and error of the electro-goniometer device was not stated, and it is questionable to use for maximal isokinetic movements. The type of electro-goniometer used by Sorensen et al. (1998) comprises of a wire that connects two blocks allowing for joint angle measures. The problem with such a design is that the bend in the wire across the knee has to be exactly the same during each contraction in order for it to be accurate. However, such precision cannot be certain during maximal muscular contractions. As well as this, these electro-goniometers are designed to measure joint angle during locomotive activities such as walking rather than maximal muscular activities such as isokinetic knee extension. Electro-goniometers were used within pilot testing however they were decided not to be used due inaccurate measurements as well as the issues stated above.

It appears that only one other study has performed a kinematic analysis of isokinetic knee extension. Verdonck et al. (1997) filmed the movement of the right knee joint axis and its angle during maximal isokinetic knee extension and flexion movements at 60°/s and 180°/s, using similar methods to the current preliminary study. Their results for the movement of the knee axis are not well presented and difficult to interpret due to a lack of descriptive information. In regards to the movement of knee joint angle and dynamometer angle they

found both angles were similar except at the end range of motion of knee extension and flexion. Here they found a 10° difference between the two angles. A major fault of this study was that a biomechanical marker was place on the participants left hip to attain true knee joint angle. The problem with this was that the left limb did not perform the knee extension movement and the study assumes that the right hip stays in the same position during isokinetic knee extension. However, this is not the case as the right hip moves throughout isokinetic knee extension. Therefore their results are not valid as they were not actually measuring true knee joint angle.

A major limitation of the current preliminary study is that true knee joint angle which comprises of ankle, knee and hip joints could not be measured due to the set up and location of the Biodex isokinetic dynamometer in the laboratory. The Biodex isokinetic dynamometer was placed in a lab that had limited space to film the knee extension movement in the frontal plane and this laboratory did not have access to other biomechanical analysis systems. When filming participants in the sagittal plane of knee extension a biomechanical marker on the hip joint was not visible as the right hip was on the opposite side of the camera, so true knee joint angle could not be measured with video analysis. As true knee joint angle cannot be measured, the magnitude of difference between true knee joint angle and dynamometer angle is unknown.

Another limitation of the current study is that the knee axis could not always be aligned exactly with the dynamometer axis due to the length of the participant's limb and the height of the dynamometer seat relative to the dynamometer axis. The seat of the Biodex System II isokinetic dynamometer is flawed as it can only be moved back a certain distance and cannot be moved up and down. Due to this, participants with long upper legs slightly overshot the dynamometer axis and their knee axis could not be aligned with it as the seat could not be moved back any further. In addition, as the seat does not move up or down the knee axes of some participant's was below the dynamometer axis. In spite of this deficiency misaligning

the knee axis by 4 cm away from the dynamometer axis in any direction does not significantly affect peak torque (Houweling & Hamzeh, 2010). Misaligning the knee axis from the dynamometer may also not affect angle measures as the knee axis is always relative to the dynamometer. This will only apply if the knee axis is in the same position each time for a given participant.

The conclusions drawn by this preliminary study are based on a set of kinematic assumptions. As the knee axis moves consistently from one repetition to another during isokinetic knee extension, it is assumed that knee joint angle is consistent. This notion is firstly dependent on the hip joint moving consistently with the knee axis. Secondly the notion above is reliant on the logic that if the hip, knee and ankle joints all move consistently then the knee joint angle moves consistently, and thus a consistent error may exist between knee joint angle and dynamometer angle. As the knee axis is the vertex of knee joint angle and that the hip and knee joints are part of the same segment, it would seem logical that if the knee axis moves consistently so would the hip joint. Further to this, human movement occurs about an axis so if all joint centres are moving consistently it would be thought that knee joint angle would also move consistently because of the movement of its associated segments and its axis of rotation. It is also important to note that knee extension is a single joint movement so such kinematic assumptions can be applied to this simplistic movement.

Further limitations of this preliminary study are that only interspersed repetitions with a 30-s rest period between the knee extension contractions was used during testing. As grouped repetitions (five successive trials) were not tested, the movement of the knee axis may have been different due to the possible metabolic fatigue associated with this protocol. Even if metabolic fatigue occurred during grouped repetitions, the movement of the knee axis may have still been consistent. Another limitation is that the biomechanical marker placed on the knee axis may have moved during muscular contractions due to movement of the surrounding

skin. If the biomechanical marker did move during muscular contractions, it would be assumed that this movement was consistent over the 50 repetitions. The biomechanical marker on the knee axis is only an estimate of knee axis centre of rotation as it moves during knee extension due to the anatomical structure of the knee. The end range of knee extension for each participant was also slightly different by 6° and was not truncated. So the movement of the knee axis towards the end range of motion is over different degree ranges between participants.

Future research could also endeavour to measure true knee joint angle rather than being reliant on dynamometer angle to infer true knee joint angle. The only other way to measure true knee joint angle would be using a portable biomechanical analysis system such as Vicon (Vicon, Denver, USA) but such analysis would be time consuming. Whether true knee joint angle can actually be measured whilst individuals perform isokinetic movements is unknown, however some researchers may want to know what true knee joint angle is during isokinetic movements.

The current preliminary study did not use a specialised harness system around the participant's waist and thighs to secure them more closely to the isokinetic dynamometer. Future research could use a specialised harness system (see Appendix D) during kinematic analysis of the knee axis during knee extension, as this may limit the range in which the knee axis can move thus further improve the consistency of the knee axis movement.

Conclusion:

The findings of this study show that the knee axis appears to move consistently from one repetition to another during isokinetic knee extension. As the knee axis moves consistently, it is assumed that the hip joint moves consistently based on biomechanical principles, and as the ankle joint has limited movement during isokinetic knee extension it is further assumed that knee joint angle is also consistent. Due to this, there might be a consistent error between knee

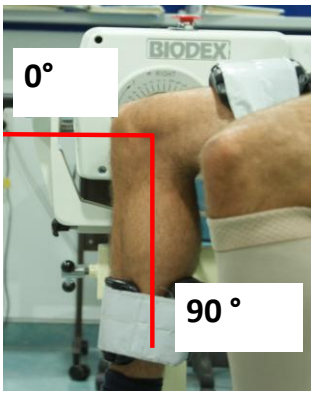
joint angle and dynamometer angle during knee extension. As this consistent error may exist, and in the absence of a suitable alternative measure of knee joint angle dynamometer angle can therefore be used to infer measures of true knee joint angle.

NB: References for Appendix A are outlined in the main references section of the thesis

Appendix B: Biodex System II isokinetic dynamometer







Appendix C: Visual analogue scale - muscle soreness

NONE |----------|WORST

Is to scale = 10 cm

Appendix D: Specialised harness system









