Strength and Inter-Limb Asymmetry: Methods of Assessment and Longitudinal Monitoring in Athletes

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Abstract

The measurement of strength and its associated asymmetries is widespread in both research and applied practice as a diagnostic tool for injury mitigation and training monitoring. Although isokinetic dynamometry is considered the gold-standard for the assessment of maximum strength, it is unclear if an optimal measurement approach exists which poses implications for interpretation of results. The time and financial burden associated with dynamometry also means it is generally unfeasible in an applied environment and so, field-based alternatives have been implemented to measure functional strength. The purpose of this research was to review and interrogate the methods associated with measuring strength and inter-limb asymmetry using lab- and field-based testing methods for athlete monitoring. The research findings may be useful in improving standards and data quality in research and practice by offering time- and cost-effective alternatives to elaborate strength testing associated with gold-standard practice.

A systematic review of the literature retrieved a total of 3,594 articles utilising methods to assess strength and inter-limb asymmetry, of which 53 articles met the inclusion criteria for the study. Various measurement strategies were employed to assess strength across a diverse range of populations, with the two most common methods of testing being isokinetic dynamometry (*n* = 25, 50%) and jumping/hopping (*n* = 28, 53%). The review identified 12 index types used to calculate inter-limb asymmetry; however, only four of them were unaffected by the limitations associated with selecting a reference limb, resulting in potentially inflated and variable scores. Interpretation was largely based on an arbitrary threshold of 10-15% but only two of the 18 articles which referenced the threshold cited original evidence for its utility in identifying ‘abnormal’ asymmetry. Asymmetry scores ranged between and within populations from approximate symmetry to asymmetries larger than 15% and variable effects were observed in relation to injury risk and performance, indicating an individual approach to asymmetry assessment and interpretation is likely necessary.

The second study aimed to establish the effect of the number and location of torque-angle measurements to assess isometric strength characteristics using isokinetic dynamometry. A simple quadratic function was used to derive the relationship between joint torque and angle in a monoarticular representation of the knee joint in simulated and experimental data. Protocols which measured torque at a single joint angle demonstrated gross underestimations

in peak torque for measurement angles that were further away from the optimal angle, particularly for narrower torque-angle profiles. Protocols which utilised multiple measurement angles identified larger errors in prediction of torque-angle characteristics for combinations with fewer measurement angles. However, in instances where an extensive protocol is not feasible, practitioners should adopt a protocol with a spread of measurements angles throughout the joint range, as well as a joint angle near the expected optimum, to improve the accuracy of torque-angle parameter predictions.

The purpose of the third study was to assess the utility of field-based alternatives to isokinetic dynamometry for the assessment of lower limb strength and inter-limb asymmetry. Maximum voluntary isometric contractions (MVIC) of the knee flexors and extensors were assessed on the dominant and non-dominant limb for comparison with a battery of unilateral functional tests: the isometric midthigh pull (IMTP), countermovement jump (CMJ) and horizontal jump (HJ). Functional tests demonstrated acceptable absolute and relative within-session reliability across the selected performance variables, but the CMJ exhibited more variability than the other two tests. Bland-Altman analyses revealed smaller systematic bias and narrower limits of agreement for the HJ compared to the other field-based tests, particularly in jump distance, which highlights it as a simple and low-cost method for assessing functional strength adaptations that can be considered meaningful and real. Although significant positive relationships were observed between knee flexor/extensor MVICs and some functional tests, predictors accounted for $\leq 30\%$ of the variance in the outcome. Between limb differences were also inconsistent between maximum and functional tests which highlights obvious task differences and strength qualities being assessed. However, inter-limb asymmetry determined by dynamometry demonstrated significant positive relationships with both maximum and functional strength. Likewise, inter-limb asymmetry determined by functional tests was significantly and positively correlated with maximum and functional strength. This indicates the potential utility of field-based alternatives for the identification of inter-limb asymmetries in muscular strength. Lastly, larger asymmetries were generally associated with better isometric strength and functional performance which indicates asymmetries of larger magnitude may be expected from stronger athletes.

The final study aimed to monitor functional strength and inter-limb asymmetry across an athletic season using field-based methods that are easily accessible and implementable in an applied environment. Vertical and horizontal jump performance and inter-limb asymmetry were assessed in team-sport athletes (N = 38) across an athletic season, and comparisons were made between sexes (male and female) and sports (netball, basketball, and hockey). Performance-based metrics (jump height and distance) for the CMJ and HJ identified sex- and sport-specific fluctuations across the season. Inter-limb asymmetry in unilateral jump performance also identified significant reductions in HJ asymmetry which coincided with improvements in HJ distance, but no changes were observed in unilateral CMJ height or CMJ asymmetry. This reiterates the diagnostic capability of the HJ to detect meaningful changes in performance and inter-limb asymmetry as indicated initially in cross-sectional data. However, the association between asymmetry magnitude and performance relates better performance with reduced asymmetries which is inconsistent with the correlations observed in the previous study. Differences in testing methods (CMJ/HJ performance metrics vs dynamometry, IMTP, CMJ and HJ performance and kinetics) and timepoints (cross-sectional vs longitudinal) as well as participant characteristics (males from one sport vs males and females from multiple sports) may, however, partly explain the lack of clarity regarding the relationship between inter-limb asymmetry and performance. Slight to moderate levels of agreement in asymmetry direction were found in the CMJ and HJ when assessed between timepoints and tests, which confirms previous indications of directional inconsistencies in which limb is favoured across measures. Therefore, seasonal fluctuations in jumping performance can be expected amongst team-sport athletes, with variation between sexes and sports. Interpretation of asymmetry magnitude without direction is cautioned against, as meaningful differences in performance can be overlooked due to directional inconsistencies within- and between-tests. Relationships between asymmetry and performance should be considered in relation to methodological decisions and sample characteristics, due to the highly variable nature of asymmetry.

Collectively, this research has demonstrated the utility of both lab- and field-based methods for the assessment of muscular strength and inter-limb asymmetry. Measurement of isometric strength characteristics using dynamometry can be improved, even when using selective measurement protocols, which reduces the barriers to gold-standard practices in the applied environment. Functional strength tests also offer provide reliable and valid indications of maximum strength and inter-limb asymmetry; however, variability should be expected between populations and tests. The magnitude and direction of inter-limb asymmetry are highly inconsistent, and so interpretation for monitoring and training purposes should be specific to the context of investigation to ensure appropriate conclusions and decision-making.

Dissemination of Research

Journal Articles

Parkinson, A. O., Apps, C. L., Morris, J. G., Barnett, C. T., & Lewis, M. G. (2021). The calculation, thresholds and reporting of inter-limb strength asymmetry: A systematic review. Journal of Sports Science & Medicine, 20(4), 594.

Oral Conference Presentations

Parkinson, A. O., Apps, C. L., Felton, P. J., and Lewis, M. G. C. (2022). The effect of measurement angle on approximations of maximum joint torque. In *ISBS Proceedings Archive*, 40(1), 543. International Society of Biomechanics in Sports, Liverpool, UK

Poster Conference Presentations

Parkinson, A. O., Felton, P. J., Lewis, M. G. C. and Apps, C. L., (2023). The effect of multiple measurement angles on the prediction of joint torque-angle parameters. International Society of Biomechanics, Fukuoka, Japan

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Key Abbreviations and Glossary

Abbreviations

MVC	Maximum Voluntary Contraction
MVIC	Maximum Voluntary Isometric Contraction
IMTP	Isometric Midthigh Pull
CMJ	Countermovement Jump
HJ	Horizontal Jump
CC	Contractile Component
PEC	Parallel Elastic Component
SEC	Series Elastic Component
RMS	Root Mean Square
CSA	Cross-Sectional Area
PCSA	Physiological Cross-Sectional Area
MRI	Magnetic Resonance Imaging
CoM	Centre of Mass
ACLR	Anterior Cruciate Ligament Reconstruction
CV	Coefficient of Variation
ICC	Intraclass Correlation Coefficient
ANOVA	Analysis of Variance

Glossary

Force-Length Properties	Muscle characteristics that describe the relationship between muscle length and force production. At the joint level, the relationship is between joint angle and torque (i.e., joint torque-angle properties)
Force-Velocity Properties	Muscle characteristics that describe the relationship between muscle shortening/lengthening velocity and force production. At the joint level, the relationship is between joint angle and torque (i.e., joint torque-angular velocity properties)
Peak Isometric Torque (T_0)	The maximum torque exerted at a joint in the absence of changes in joint angle
Optimal Angle (θ_{opt})	The joint angle at which peak isometric torque occurs
Width (k_2)	A scaling factor to describe the curvature of the joint torque-angle profile

Chapter 1: General Introduction

1.1 Area of Study

Skeletal muscle has been recognised as the operating machinery responsible for human movement for more than 2000 years, with Aristotle of Ancient Greece (384-322 BCE, *De Motu Animalium*) describing the distribution of air in the body (*pneuma*) and invasion of an animal spirit (*spiritus animalium*) into the muscles. Later, Galen (129-201 CE, *De Tremore*) discovered arteries containing blood rather than air and he recognised muscles as true organs of voluntary movement able to contract and relax. His work was widely accepted in both medicine and religion until the Renaissance when Vasalius (1514-1564, *De Humano Corporis Fabrica*) published his works on human anatomy, and contractile power within the muscle was discovered. Later discoveries, including morphological changes without changes in muscle volume during contraction (Swammerdam 1663, c.f. Needham, 1971), neural signalling from the brain to the muscles (Croone 1664, *De Ratione Motus Musculorum*) and detailed descriptions of muscular and tendinous structures (Stensen 1664, *De Musculis et Glandulis Observationem Specimen* and 1667, *Elementorum Myologiae Specimen, seu musculi descripto geometrica*) have developed and informed current knowledge of human anatomy and function in circulation today.

Theories of muscular contraction and force production have developed since the early 20th century, with contraction initially believed to occur by folding of long protein filaments and later, due to shortening of the myosin filaments. Current theory is underpinned by the sliding filament theory proposed by Hugh Huxley (1953) following his observations of two distinct filaments (thin and thick) in the sarcomere, today referred to as actin (thin) and myosin (thick). The thick filaments were observed in the I-band region of myofibrils, while the thin filaments were visible in both the A- and I-bands. Shortly after, the length of the thick filament was found to be unaltered by stretch or contraction (except in extreme shortening), indicating the relative sliding of filaments are in fact responsible for muscle length changes (Huxley & Niedergerke, 1954; Huxley & Hanson, 1954). The molecular mechanism behind muscular contraction was still unknown, however, which lead to the mathematical formulation of the cross-bridge model (Huxley, 1957). Interaction between myofilaments was thought to occur by temporary binding of side pieces (later named cross-bridges) on one filament to periodically arranged active sites on the other. The cross-bridge model is still the accepted mechanism of contraction, with each cross-bridge cycle associated with the release of energy by hydrolysation of one Adenosine-Triphosphate molecule; however, it fails to explain history-dependent properties of skeletal muscle, such as residual force enhancement (increase in isometric force following muscle lengthening) and depression (reduction in isometric force following muscle shortening; Herzog, 1998) The 3-filament model, which includes an additional passive component, Titin, has been proposed more recently to address such limitations as its activation-sensitive stiffness explains residual force enhancement and depression and passive force enhancement (Joumaa et al., 2007, 2008; Leonard et al., 2010; Walcott & Herzog, 2008).

Strength is commonly used to describe the force-producing capacity of skeletal muscle which is influential for general function and human locomotion as well as athletic performance. Maximum strength can be described as the maximum capacity of the muscles to exert force on the skeletal system which is specific to the state of muscle activation and varies with muscle length and velocity (Frey-Law et al., 2012). Thus, the measurement of strength is dependent on the movement environment and describes the maximum capacity for exerting force within a given scenario. Activation of the muscle initiates an interaction between actin and myosin myofilaments, whereby the sarcomere attempts to shorten; however, the muscle action (isometric, concentric, or eccentric) is ultimately determined by the ratio of internal muscle forces to external load. Isometric strength can be determined during static tasks whereby the muscular force is in equilibrium with an external force and changes in the joint position are resisted (internal force = external force). The magnitude of force reflects the interaction of myofilaments within the sarcomere and the number of available cross-bridges, which varies with muscle length and is optimal near the resting length of the muscle (Edman & Reggiani, 1987; Gordon et al., 1966; Huxley, 1957; Huxley & Simmons, 1971). Dynamic strength can be determined when internal and external forces are unbalanced which results in concentric shortening (internal force > external force) or eccentric lengthening (internal force < external force) of the muscle and subsequent changes in the joint position. The force exerted during dynamic work is dependent on the linear velocity of contraction, with increasing concentric velocities associated with a non-linear decline in force below isometric force due to the reduction in cross-bridge force and availability (Edman, 1988; Edman et al., 1976; Fenn & Marsh, 1935; Hill, 1938). Eccentric contractions, on the other hand, have a higher force-output that is increased or maintained as the linear velocity is increased (Edman, 1988; Harry et al., 1990; Katz, 1939). When examined *in vivo,* however, the configuration of skeletal muscle with respect to skeletal system must be considered when assessing muscular strength and function.

The assessment of muscle and joint function became possible in the 1960s with the introduction of isokinetic exercise (Hislop & Perrine, 1967 as cited by Westing et al., 1991) whereby dynamic strength could be assessed as the limb moved throughout large ranges of motion under constant angular velocities. Today, isokinetic dynamometry is considered the gold-standard method for measuring isometric and isokinetic strength due to its high reliability in peak torque (de Araujo Ribeiro Alvares et al., 2015; Maffiuletti et al., 2007; Tsiros et al., 2011) and its use is widespread in testing, training and rehabilitation (Bagordo et al., 2020; Brown & Whitehurst, 2003; Herbawi et al., 2022; Knezevic et al., 2014; Silva et al., 2015; Sørensen et al., 2021). The terms 'torque' and 'moment' both describe the rotational effects resulting from the application of muscle forces at a distance from the axis of rotation; however, mechanically, they describe different force applications (Baltzopoulos, 2017). With respect to isokinetic dynamometry, both terms can be appropriate, with 'moment' describing the bending effects on the dynamometer crank arm and 'torque' describing the twisting effect on the central rod of the dynamometer. As such, both terms will be used hereafter with preference given to the term used in the immediate literature.

The effect of joint angle (joint moment-angle) and angular velocity (joint moment-velocity) on joint moment has also been investigated in various muscle groups and populations (Brughelli et al., 2010; Frasson et al., 2007; Herzog et al., 1991; Janicijevic et al., 2020; Kozinc et al., 2021; Kulig et al., 1984; Thom et al., 2007), demonstrating large variability in moment-angle-velocity characteristics. Although, dynamometers allow for assessments of all the major joints in the human body, testing generally involves isolation of a single-joint which limits ecological validity. In addition, measurement error associated with subject position, joint/crank axis misalignment, lack of familiarisation, and correction of the gravitational moment necessitate standardised protocols and technical expertise (Appen & Duncan, 1986; Arampatzis et al., 2004, 2005; Dirnberger et al., 2012; Nugent et al., 2015; Winter et al., 1981). Yet, lengthy experimental protocols and expensive equipment are generally unfeasible in an applied environment. Resultantly, functional tests, such as the isometric midthigh pull and jumping/hopping, have been proposed as a cost- and time-effective alternative to typical lab-based testing. High reliability has been demonstrated amongst functional testing methods; however, variability has been observed between methods, such that some tests and equipment may not have adequate precision to detect meaningful differences (Balsalobre-Fernández et al., 2019; Bishop et al., 2019c; Bohannon et al., 2011; Comyns et al., 2023; Dos'Santos et al., 2017c; Maulder & Cronin, 2005; Mentiplay et al., 2015; Pérez-Castilla et al., 2021). Furthermore, the relationship between functional performance and maximum strength determined by isokinetic dynamometry is unclear (English et al., 2006; Greenberger & Paterno, 1995; Jones & Bampouras, 2010; Newton et al., 2006; Östenberg et al., 1998; Petschnig et al., 1998), yet the use of field-based alternatives for the assessment of functional strength remains.

Assessment of inter-limb asymmetry, referring to differences in performance between limbs, has become commonplace for athlete monitoring and injury rehabilitation (Bishop et al., 2021c; Fort-Vanmeerhaeghe et al., 2021; Jordan & Bishop, 2023; Jordan et al., 2015; Patterson et al., 2020) due to reported associations with increased injury risk and reduced performance (Bishop et al., 2019a, 2019b, 2021b; Brumitt et al., 2020; Fort-Vanmeerhaeghe et al., 2020, 2022; MacSweeney et al., 2023; Madruga-Parera et al., 2020, 2021; Steidl-Müller et al., 2018). Inter-limb asymmetries in athletes may reflect the sporting environment and exposure to sport-specific tasks. Repeated exposure to asymmetric motor patterns, such as kicking or throwing, may therefore result in larger inter-limb asymmetries compared to sports largely characterised by symmetrical tasks (Kalata et al., 2020). Strength asymmetries above 10-15% are often considered to be problematic (Barber et al., 1992; Kyritsis et al., 2016; Rohman et al., 2015) and various training strategies have been recommended to reduce the magnitude of inter-limb differences (Bishop et al., 2018b; Gonzalo-Skok et al., 2019). However, interpretation of asymmetry scores using arbitrary thresholds has been challenged in recent literature due to the task-, metric- and population-specific nature of asymmetry (Bishop et al., 2019c, 2019b; Dos'Santos et al., 2017c; Read et al., 2021). Furthermore, inconsistent terminology and variability in the calculation of scores between investigations creates confusion for the interpretation of asymmetry data with respect to the wider literature. Specifically, some indexes normalise the difference between two limbs by a reference limb value which is assumed to be the stronger of the two, whilst others divide the contralateral limb value or a statistic of the two by the reference limb (Bishop et al., 2016). However, indexes which select a reference limb are prone to artificial inflation and have been shown to produce inconsistent scores in scenarios where the contralateral limb outperforms the reference limb (Bishop et al., 2016). In addition, some indexes fail to identify the direction of asymmetry (i.e., which limb is stronger or favoured) which is problematic when making repeated measures. Longitudinal data have shown variability in asymmetry direction over an athletic season as well as between tasks and variables, such that assessment of the magnitude alone can create a false impression of consistency in asymmetry over time (Bishop et al., 2020b, 2021c; Fort-Vanmeerhaeghe et al., 2021). Thus, the range of methods for calculation and interpretation of asymmetry scores requires further investigation to ascertain their usefulness in determining inter-limb differences.

1.2 Statement of Purpose

The assessment of inter-limb asymmetry in strength has become increasingly popular in both research and applied practice; however, there is a lack of clarity with regards to measurement and calculation which has led to inconsistent and flawed methodology and interpretation. The potential implications of methodological decisions also require further exploration to establish the practical application and utility of various methods of assessment across both research and applied environments. Thus, the purpose of this research was to review and interrogate the methods associated with measuring strength and inter-limb asymmetry using lab- and field-based testing methods for athlete monitoring.

To achieve this, a systematic review of the literature was first conducted to collate information of the various measurement techniques in use for the assessment of inter-limb strength asymmetry, including test types and calculation of asymmetry, as well as normative data using documented methods (Chapter 3). Included articles adopted various testing methods, including isokinetic dynamometry and numerous functional alternatives, such as jumping/hopping and multi-joint strength testing. Despite its gold-standard status for measuring maximum strength, there was no consistency in measurement protocol for isokinetic dynamometry. Consequently, an investigation was conducted to assess the effect of the number and location of measurement joint angles in simulated and experimental datasets, with the aim of improving methodological procedures for predicting isometric strength characteristics (Chapter 5). Findings from both investigations were used to inform methodological decisions for the assessment of strength and inter-limb asymmetry in athletes using lab- and field-based methods.

Methods were then assessed for within-session reliability and comparability to one another to establish their utility in applied practice (Chapter 6). Finally, a longitudinal study was designed to address questions regarding seasonal fluctuations in asymmetry magnitude and direction in athletes using simple, cost-effective methods that are accessible in the field (Chapter 7).

1.3 Thesis Structure

Chapter 1: General Introduction

A brief overview of the relevant literature and rationale for this thesis, including an outline of its purpose and structure.

Chapter 2: Literature Review on Muscular Strength: Structure, Function, and Methods of Assessment

Review of the literature related to the structure and architecture of skeletal muscle, as well as functional and mechanical characteristics that influence the human body's capacity for movement and performance. Experimental and theoretical approaches to the assessment of muscular strength are also discussed. This review is a necessary precursor for the understanding and appropriate assessment of asymmetry in strength-based metrics.

Chapter 3: Systematic Review on the Calculation, Thresholds and Reporting of Inter-Limb Strength Asymmetry

A systematic review of the literature on inter-limb asymmetries in strength, which discusses the various methods of assessment for strength and associated asymmetries and summarises normative data across targeted samples.

Chapter 4: General Methodology

A detailed overview of the key methodologies used in the experimental research conducted for this thesis, including procedures for data simulation, and collection and analysis of experimental datasets.

Chapter 5: Joint Torque-Angle Characteristics: Assessing the Accuracy of Experimental Determination

An investigation of methodological approaches used for the assessment of isometric strength using the gold-standard method, isokinetic dynamometry. Both simulated and experimental datasets were investigated to assess the potential errors associated with various measurement protocols which vary in both the number and location of measured joint angles.

Chapter 6: Strength and Inter-Limb Asymmetry: Reliability of Functional Tests and Relationships with Isokinetic Dynamometry

A cross-sectional study to assess inter-limb asymmetry in maximum and functional strength amongst competitive athletes. Within-session reliability and correlations between testing methods are explored and discussed in relation to their utility for monitoring performance and asymmetry in an applied setting.

Chapter 7: Jumping Performance and Inter-Limb Asymmetries: A Season-Long Study in University Team-Sport Athletes

A longitudinal study in competitive athletes investigating inter-limb asymmetries in functional strength determined by vertical and horizontal jumping. The concept of longitudinal fluctuation in asymmetry magnitude and direction is explored and results are discussed in relation to sex and sport.

Chapter 8: General Discussion

A summary of the thesis is provided, including a discussion of the key findings and practical applications. Limitations of the experimental work are discussed and recommendations for future work are provided.

Chapter 2: Literature Review on Muscular Strength: Structure, Function and Methods of Assessment

2.1 Chapter Overview

The following chapter provides an overview of the literature on muscle strength, from the structure of skeletal muscle to function in human movement and performance. Literature on the mechanical properties of muscle from animal models, cadavers and living participants are summarised. Structural and architectural characteristics that underpin the mechanical behaviour of skeletal muscle in human movement are also described and compared between muscles and individuals. Finally, experimental and theoretical approaches to the *in vivo* measurement of maximum and functional strength are detailed.

2.2 Mechanical Properties of Strength

Muscles are the motors of human movement; producing force in response to stimuli from the nervous system and acting on the skeletal system to enable movement and provide joint and whole-body stability. The mechanical nature of skeletal muscle is captured by A.V. Hill's, (1938) 3-component model (**Figure 2.1**) comprised of a contractile component (CC), parallel elastic component (PEC) and series elastic element (SEC). Although specific structures within the muscle are commonly attributed to each component, it is emphasised that this model represents behavioural characteristics within the muscle-tendon unit and not specific anatomical structures.

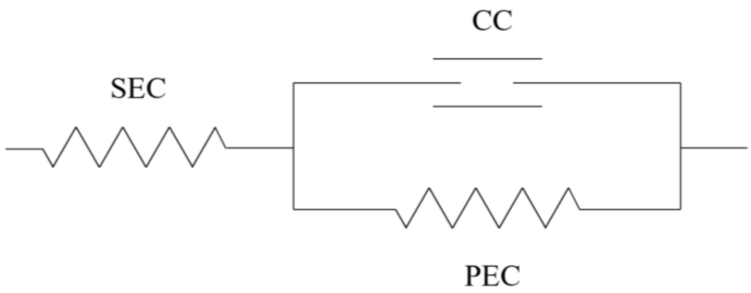

Figure 2.1 Hill muscle model, depicting the contractile component (CC), series elastic component (SEC) and parallel elastic component (PEC)

The CC is primarily responsible for the active force produced within the muscle which is driven by neural activation. Stimulation of the muscle fibre enables the interaction of myofilaments in the sarcomere and in turn, muscular contraction. Changes in muscle length occur in response to the formation of cross-bridges between actin and myosin, which pull the actin filament across myosin (Huxley & Niedergerke, 1954; Huxley &

Hanson, 1954). Muscle length during activation is also influenced by the relative magnitude of internal to external forces which results in either isometric, concentric, or eccentric loading. During isometric work, internal and external forces are balanced, and so muscle length remains constant. Comparatively, muscle shortening occurs in instances when the internal force exceeds the external force (concentric), and muscle lengthening occurs when the external force exceeds the internal force (eccentric).

Force generation is determined by mechanical properties such that force output varies with respect to muscle length and velocity of shortening. Therefore, the maximum capacity to produce force (i.e., strength) may vary in any given scenario due to force-length (or joint moment-angle) and force-velocity (or joint moment-angular velocity) properties.

2.2.1 Force-Length Properties

The isometric length-tension relation for an activated isolated muscle fibre was first demonstrated by Ramsey & Street, (1940) in the frog semitendinosus muscle. Maximum tension was observed in the sarcomere when electrically stimulated at its resting length. A plateau in tension was achieved for lengths near the optimal fibre length and tension decreased at lengths beyond the plateau region. Specifically, active tension decreased almost linearly from maximum at resting length (100%) to zero at twice resting length (200%) and the decline for shorter lengths (70%) was approximately exponential (**Figure 2.2**).

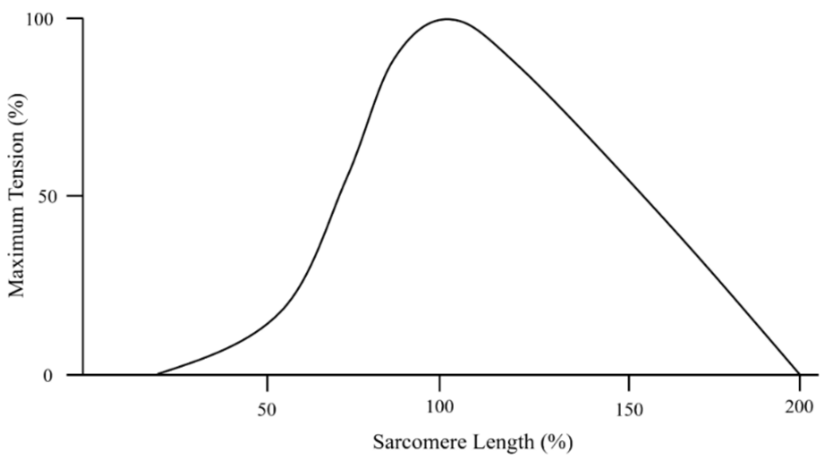

Figure 2.2 Length-tension relationship of isolated muscle fibres of the frog semitendinosus (adapted from Ramsey & Street, 1940)

As per the cross-bridge theory, this relationship can be directly determined from the number of available cross-bridges, with force generation determined by the amount of overlap between actin and myosin (Huxley & Niedergerke, 1954). Force production in the frogs' isolated muscle fibre was found to be optimal at sarcomere lengths between 2.05-2.2 µm and declined as the number of available cross-bridges decreased on the so-called descending limb (Gordon et al., 1966). Based on previous research, force was initially expected to diminish to zero at lengths greater than the sum of thin and thick filaments (around 3.5 µm; Ramsey & Street, 1940). However, latter findings by A. F. Huxley & Peachey, (1961) demonstrated tension in the sarcomere at 4µm when the two filaments do not overlap sufficiently to form cross-bridges. Sarcomere non-uniformity was proposed as a possible explanation for this, indicating some overlap between myofilaments at the fibre ends which were not stretched as far as the main body of the fibre. Gordon et al., (1966) were able to overcome instability of sarcomeres on the descending limb by examining the central region of the fibre where sarcomeres were sufficiently uniform.

Albeit correct, the force-length relationship of an isolated sarcomere as depicted by Gordon et al., (1966) does not represent the force-length properties of the fibre (or muscle) *in vivo*. Namely, the intact muscle demonstrates a smaller peak force at the optimal length and a larger operating range over which nonzero forces can be obtained (Herzog & ter Keurs, 1988b; **Figure 2.3**). The descending limb also follows a more curved path as sarcomere length does not remain constant throughout the whole fibre. In a study by Ettema & Huijing, (1994), experimental data for the rat gastrocnemius was closely replicated by models with either 1) distributed fibre optimum lengths (same absolute fibre length at a given muscle length) or 2) distributed absolute fibre lengths at a given muscle length (same optimum length). Distributed fibre lengths on the active force-length curve can, therefore, partly explain differences in the *in vitro* versus *in vivo* profile. Force-length properties of animal muscle also differ to those of human muscle, with humans demonstrating longer actin lengths than animals, shifting the force-length profile to the right (Herzog, 1996; Walker & Schrodt, 1974).

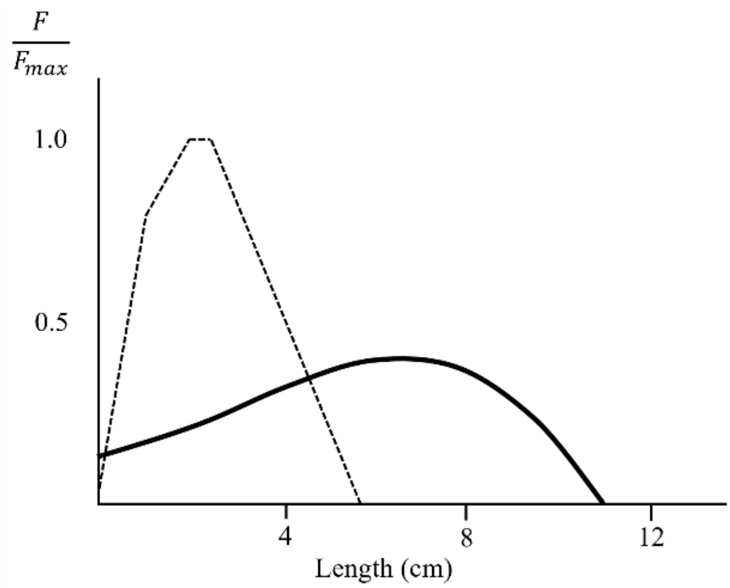

Figure 2.3 Comparison between the theoretical *in vitro* force-length relation (dashed line) and the normalised force-length relation of the rectus femoris muscle *in vivo* (solid line; adapted from Herzog & ter Keurs, 1988b)

Measurement of *in vivo* moment-length relationships in humans is possible using isokinetic dynamometry and the force-length properties of selected muscles can be calculated from experimental data (Herzog, 1988; Herzog & ter Keurs, 1988a). *In vivo*, the range of muscle fibres lengths is limited to the physiologically realistic joint range of motion and so, the intact muscle tends to operate on only part of the force-length (or moment-length) profile. In a review of human strength curves, Kulig et al., (1984) described the maximum isometric force (or moment) exerted by synergistic muscle groups as a function of their length at different joint angles. The various joints were shown to exhibit three distinct profiles (**Figure 2.4**); 1) ascending (increasing moment with increasing joint angle, e.g., knee flexion), 2) descending (decreasing moment with increasing joint angle, e.g., knee extension) or 3) ascending-descending profiles (increasing then decreasing moment with increasing joint angle, e.g., shoulder extension). The region of the curve that is expressed has functional consequences for human movement, with muscles that operate on the ascending limb undergoing regular stretch-shortening cycles while muscles operating on the descending limb typically undergo shorten-stretch cycles (Rassier et al., 1999).

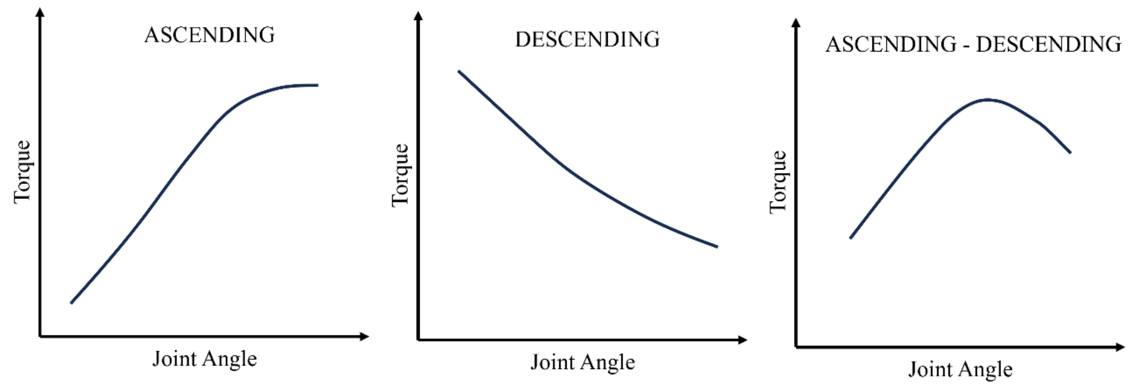

Figure 2.4 Human strength curves observed by Kulig et al., (1984) exhibited a) ascending (increasing torque with increasing joint angle), b) descending (decreasing torque with increasing joint angle) or 3) ascending-descending profiles (increasing then decreasing torque with increasing joint angle)

Although fibres of the same human muscle demonstrate similarities in muscle length/fibre length ratios and architecture (Wickiewicz et al., 1983), muscle-specific force-length properties have been shown to vary between individuals (Herzog & ter Keurs, 1988b; Winter & Challis, 2008). Herzog & ter Keurs, (1988b) measured *in vivo* force-length properties of the human rectus femoris muscle in six male subjects, with all but one demonstrating non-linear profiles between 3.5-7.5 cm changes in fibre length. The exertion of force at similar lengths was highly variable between subjects, indicating the presence of individual differences in force-length characteristics. This was later confirmed in an investigation of the intact rectus femoris muscle in cyclists and runners during maximal voluntary knee extensions (Herzog et al., 1991). The cyclists operated on the descending limb and were relatively stronger at short muscle lengths (negative relationship between joint moment and muscle length, **Figure 2.4b**) whereas the runners operated on the ascending limb and were relatively stronger at long muscle lengths (positive relationship between joint moment and muscle length, **Figure 2.4a**). Resultantly, joint moment-length (or force-length) characteristics are expected to reflect the functional demands imposed on the muscle, with the muscle expected to achieve more force at lengths it is chronically exposed to.

2.2.2 Force-Velocity Properties

The ability of the muscle to produce force is also influenced by the velocity of contraction. The force-velocity relation during shortening (concentric) contractions was first described mathematically in animal muscle in the 1930s (Fenn & Marsh, 1935; Hill, 1938). Such investigations demonstrate a non-linear decline in tension with increasing velocity of shortening. This relationship, represented as an exponential function (Fenn & Marsh, 1935) or rectangular hyperbola (Hill, 1938), proved to be consistent with the sliding filament model and independent behaviour of cross-bridges as force generators (Huxley, 1957; Huxley & Niedergerke, 1954; Huxley & Hanson, 1954).

Still widely popular today, the equation proposed by Hill, (1938) demonstrates maximum tension when linear velocity is zero (isometric) and a steep drop off in tension at high concentric velocities (**Figure 2.5**). The hyperbolic nature of the force-velocity relation in whole muscle was later confirmed on isolated single muscle fibres at low to intermediate forces (Edman et al., 1976). Inconsistent behaviour in the high-force/low-velocity range, however, indicated load-specific changes in the kinetics of cross-bridge function (Edman et al., 1976). Edman (1988) identified a breakpoint near 78% of the measured isometric force due to the high density of attached cross-bridges at lower concentric velocities, and instead proposed a double hyperbolic force-velocity curve.

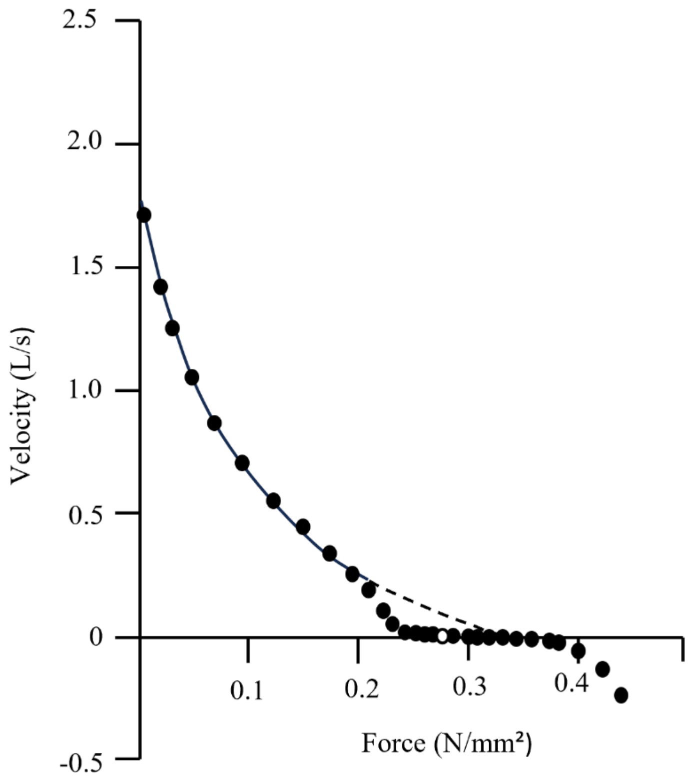

Figure 2.5 Force-velocity relation in a single muscle fibre which displays a breakpoint around 78% of measured isometric force (hollow circle) and deviation from the hyperbolic function (dashed line; adapted from Edman, 1988).

The force-velocity relation of lengthening (eccentric) contractions is less clear than that during isometric or concentric work. Early studies by Katz, (1939) demonstrated an increase in force on the ‘negative' portion of the curve and predictions from the cross-bridge model indicated an asymptote in force at high lengthening velocities (Huxley, 1957). Experimental studies have since observed both increased and maintained levels of force with increasing lengthening velocities up to a critical speed, at which point force plateaus at roughly 1.5-1.9 times the maximal isometric value (Edman, 1988; Harry et al., 1990; Katz, 1939).

The intact skeletal muscle demonstrates similar concentric behaviour to the *in vitro* force-velocity relationship yet, findings indicate deviations during eccentric contractions (Hageman et al., 1988; Westing et al., 1988). Specifically, maximal voluntary eccentric moment does not increase much, if at all, above the isometric moment and force is increased when the muscle is electrically stimulated (**Figure 2.6**; Dudley et al., 1990; Pain et al., 2013; Seger & Thorstensson, 2000; Webber & Kriellaars, 1997; Westing et al., 1990). Reduced activation during muscle lengthening indicates this is an inhibitory mechanism of the neuromuscular system to protect against injury (Babault et al., 2003; Del Valle & Thomas, 2005; Kellis & Baltzopoulos, 1997; Westing et al., 1991a). The non-hyperbolic behaviour of the *in vivo* force-velocity relationship due to differential activation can, however, be accounted for when estimating joint torque in high-force regions of the curve (Yeadon et al., 2006).

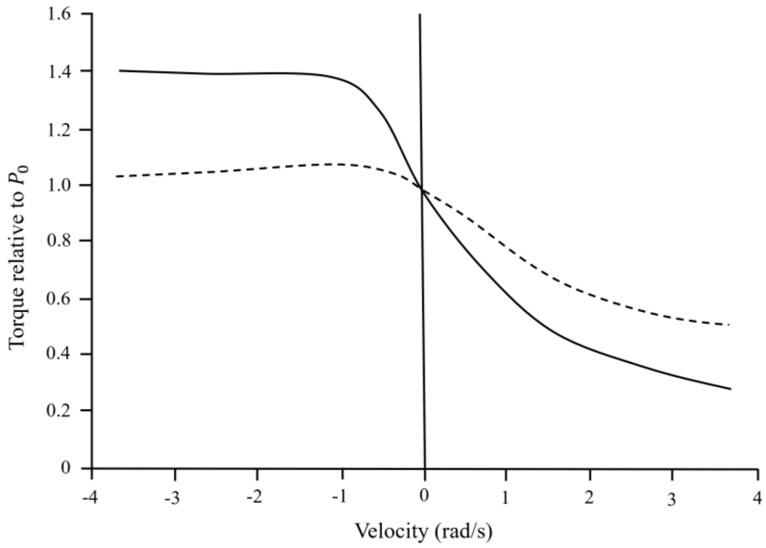

Figure 2.6 Torque-velocity relation (normalised to measured isometric, P_0) of knee extensor muscle group during maximal voluntary (dashed line) or artificially stimulated (solid line) concentric (positive) and eccentric (negative) loading *in vivo* (adapted from Dudley et al., 1990)

Deviations from the typical hyperbolic force-velocity behaviour have also been documented for multi-joint actions, which have instead been described using linear relationships (Alcazar et al., 2018; Bobbert, 2012; Dorel et al., 2005; Jaric, 2015; Jiménez-Reyes et al., 2014; Samozino et al., 2012, 2013). Recent findings, however, indicate that the observed linearity may be the result of performing multi-joint tests over a narrow region at high to moderate forces (Alcazar et al., 2019). A novel equation has since been proposed which incorporates the linear region observed from high to moderate forces as well as the curvilinear region from moderate to zero forces (Alcazar et al., 2022, 2023).

2.2.3 Power-Velocity Properties

The power-velocity relationship can be derived from the force-velocity profile since power is the scalar product of force and velocity and is commonly represented as a simple polynomial (Dorel, 2018; Dorel et al., 2005; Hintzy et al., 1999). Accordingly, power is zero during isometric contractions (v = 0) and during maximal shortening (F = 0) and reaches its peak when optimal values of force and velocity are obtained. Maximal muscle power has been shown in the frog semimembranosus during jumping to correspond to roughly 30% of the maximal shortening velocity, enabling them to optimise power output when escaping predators (Lutz & Rome, 1994). Sprint running and cycling and jump performance have previously been associated with maximal power in athletes (Dorel et al., 2005; Jiménez-Reyes et al., 2014, 2018; Samozino et al., 2013; Vandewalle et al., 1987). Vandewalle et al., (1987) reported peak power values up to 17.1 $W \cdot kg^{-1}$ in elite power athletes and reduced maximal force, velocity and power amongst endurance athletes and recreational participants. This corresponds with muscle biopsy data which demonstrate a higher percentage of fast-twitch muscle fibres in power athletes and subsequently maximal power at higher velocities compared to endurance athletes (Clarkson et al., 1980; MacIntosh et al., 1993; Tihanyi et al., 1982). Thus, maximal power is indicative of training background and genetic factors.

2.3 Physical and Neuromuscular Determinants of Strength

Mechanical properties of skeletal muscle underpin the relationship between force production and muscle length and contractile velocity. For the intact muscle, the maximum capacity to exert force on the skeletal system (i.e., strength) is also influenced by anatomical characteristics, neural activation, connective tissue elasticity, and the structural configuration of the muscle-tendon unit within the musculoskeletal system.

2.3.1 Muscle Structure and Architecture

The muscle fibre consists of multiple sarcomeres aligned in-series, with the Z-line marking the threshold at which one sarcomere ends and another begins within each myofibril. The long, cylindrical fibres run parallel to one another and are covered by a fine, sheath-like membrane, the endomysium. Muscle fascicles, containing up to 200 muscle fibres under a dense connective sheath (perimysium), are bundled together within the muscle belly and covered by a fibrous tissue, the epimysium. As well as providing structure, connective tissue within the muscle enables delivery of the blood supply and neural impulses via capillaries and nerves and transfer of tension from muscle to bone.

Muscle architecture, defined as the arrangement and organisation of muscle fibres (Gans, 1982) influences function by modulating the exertion of force on the skeletal system at the origin or insertion. Two main fibre arrangements are found in skeletal muscle; parallel fibres, which run along the long axis of the muscle and have similar lengths to the whole muscle, and pennate fibres, which run diagonally with respect to a central tendon and are relatively short compared to the muscle length.

The pennation angle, describes the angle of the muscle fibre with respect to the line of action from origin to insertion so, in parallel (or fusiform) fibres, the pennation angle is equal to zero. Due to the arrangement of parallel fibres, the force transferred to the tendon is equal to the muscle fibre force, and directly proportional to the anatomical cross-sectional area (CSA) measured perpendicular to the long axis of the segment. Muscles fibres at a pennation angle greater than zero can run at one (unipennate), two (bipennate), or multiple (multipennate) angles from the central tendon. As a result, the relationship between tendon force and CSA is not upheld for pennate fibres. Instead, tendon force is directly proportional to the physiological cross-sectional area (PCSA), which accounts for pennation angle by measuring in the plane perpendicular to the line of action of the muscle fibres (Maganaris, 2001).

Parallel fibred muscles tend to have longer lengths but smaller PCSAs and so, can exert force over a larger operating range (Lieber & Fridén, 2000; Ward et al., 2009). Parallel fibres also contract at higher velocities as they contain more sarcomeres in-series. Contrastingly, muscles with pennate fibres tend to have larger PCSAs due to the increased number of sarcomeres in-parallel (Kawakami et al., 1995; Ward et al., 2009). Resultantly, they can produce more force but over a smaller operating range and at slower angular velocities. As pennation angle increases, more fibres can be packed into a muscle, thus increasing the force-production capabilities of the muscle without increasing muscle thickness; yet not all the fibre force can be transferred to the tendon. Tendon force can be calculated as force produced by the muscle fibres multiplied by the cosine of the pennation angle. Therefore, as the line of action pivots further from the longitudinal axis of the limb, the cosine term decreases resulting in reduced fibre force being transferred to the external tendon.

Pennation angle has been shown to vary with changes in muscle length that occur when progressing throughout the normal physiological joint range of motion and during muscular contraction (Fukunaga et al., 1997a; Kawakami et al., 1998). For instance, Fukunaga et al., (1997a), reported a 27% decline in vastus lateralis fascicle length accompanied by an increasing pennation angle as the knee progressed passively from flexion to extension, and this effect was greater (30%) during active state contractions. As the transfer of force to the tendon from pennate fibres is reduced by a factor of cosθ (where θ = pennation angle), the force-producing capacity of fibres with larger pennation angles is reduced (Fukunaga et al., 1997a; Kawakami et al., 1998). Nonetheless, the effect of fibre pennation angle on force-producing capabilities may be negligible for muscles with relatively small pennation angles, which are observed at rest and low force contractions (Fukunaga et al., 1997a). Furthermore, the effect of increasing pennation angle on fibre length is such that fibres contract at slower velocities than the whole muscle and more fibres can be arranged in parallel (increased PCSA), which enables fibres to maintain force output (Gans & Gaunt, 1991).

Scanning techniques such as magnetic resonance imaging (MRI) and ultrasound can be used to determine muscle architecture, including muscle length, pennation angle, and PCSA, and provides crucial insight into the role of individual muscles in human movement. Ward et al., (2009) extracted twenty-seven lower limb muscles from a sample of twenty human specimens per muscle and recorded architectural characteristics and differences between muscles (**Figure 2.7**). The vastus lateralis, for example, yielded the largest mass (375.9 ± 137.2 g), but a smaller PCSA than muscles with smaller mass and fibre lengths but larger pennation angles (e.g., soleus). When comparing muscle groups at the knee, the knee flexors and extensors demonstrate similar mean fibre lengths (9.3 ± 2.6 cm and 9.3 ± 2.1 cm, respectively), but increased mass and pennation angles in the extensor muscles contribute to a significantly larger total PCSA (88.4 ± 30.5 cm^2 vs 40.1

± 13.6 cm^2). Such architectural characteristics reflect the functional role of the musculature, with the knee flexors adapted for large joint excursions and high angular velocities, making them increasingly useful for powerful, dynamic movements. The knee extensors (particularly the vastus lateralis), on the other hand, are suited to forceful antigravity contractions due to increased PCSA. *In vivo* investigations of muscle architecture in humans demonstrate variability in pennation angles between and within the same muscle, with differences observed in relation to characteristics such as age, sex, and training (Aagaard et al., 2001; Kawakami et al., 1993; Kubo et al., 2003; Narici et al., 2003b) as well as to contraction intensity and joint angle (Fukunaga et al., 1997b; Maganaris et al., 1998b; Maganaris, 2001; Narici et al., 1996).

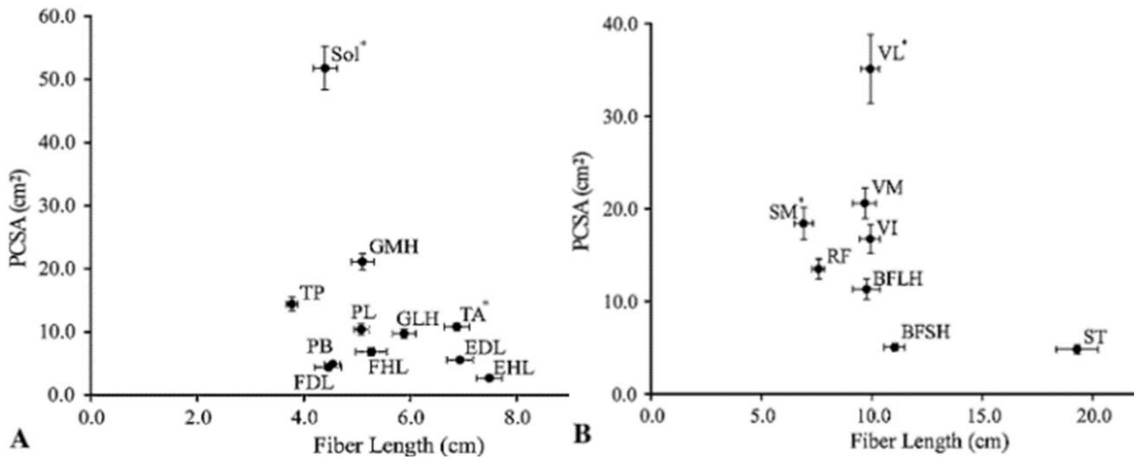

Figure 2.7 Muscle fibre length versus physiological cross-sectional area (PCSA) for the a) ankle and b) knee (as mean ± standard error).Sol = soleus; GMH = gastrocnemius medial head; TP = tibialis posterior; PL = peroneus longus; PB = peroneus brevis; FHL = flexor hallucis longus; FDL = flexor digitorum longus; TA = tibialis anterior; EHL = extensor hallucis longus; EDL = extensor digitorum longus; VL = vastus lateralis; VM = vastus medialis; VI = vastus intermedius; RF = rectus femoris; ST = semitendinosus; SM = semimembranosus; BFLH = biceps femoris lateral head; BFSH = biceps femoris short head.* = largest PCSA ($p < 0.05$) within muscle group (Ward et al., 2009, p1079)

Specific tension, quantified as force/PCSA, reflects the intrinsic force-generating potential of the muscle per unit of cross-sectional area (N·cm^{-2}). Type I (slow-twitch) fibres exhibit lower specific tension and are more fatigue-resistant, while type II fibres exhibit higher specific tension and are designed for power and strength. For instance, Bottinelli et al., (1996) found that the maximum specific tension of type II fibres can be up to 50% greater than that of type I fibres due to their larger myofibrillar density and different myosin heavy chain isoforms. Accordingly, elite endurance athletes possess predominantly type I fibres compared to power athletes who have more type II fibres (Costill et al., 1976; Fry et al., 2003). In a comparison of the vastus lateralis in young and old adults of either active or sedentary status, young and active old adults demonstrated increased specific tension of type II fibres than for type I fibres, but this was not the case for sedentary old adults. Thus, the maximum force-generating potential of a type II muscle fibres is increased in active older adults due to larger muscle size (CSA) and specific tension compared to their sedentary counterparts (Larsson et al., 1997).

2.3.2 Neural Activation

Activation of skeletal muscle is initiated by the central nervous system which transmits action potentials to the muscle fibres via the peripheral nervous system. Depolarisation across the sarcolemma and subsequent binding of calcium to troponin enables the interaction of myofilaments in the sarcomere and in turn, muscular contraction. The maximum moment achieved at a joint depends on the level of activation of the surrounding musculature, with increased explosive muscle strength associated with increased neural drive following resistance training (Aagaard et al., 2002). This is substantiated by evidence of disproportionate reductions in muscle strength relative to loss in muscle mass in response to aging, immobilisation and disuse (Macaluso et al., 2002; Narici et al., 2003a; Stevens et al., 2006; Williams et al., 2005). Voluntary muscle moment can be increased with superimposed tetanic stimulation, indicating not all motor units are stimulated during voluntary activation of the muscle (Babault et al., 2001, 2003). Differences in EMG activity are also observed between contraction modes, such that neural activation is lower during eccentric loading than concentric loading at the same velocity (Babault et al., 2001; Kellis & Baltzopoulos, 1997, 1998; Westing et al., 1991a) and is highest during isometric conditions (Babault et al., 2001, 2003).

Isokinetic dynamometry is commonly used to measure maximum strength at a joint, but measurements provide net joint moment, including contributions from both agonistic and antagonistic muscles (Kellis & Baltzopoulos, 1997). Antagonistic muscles provide necessary stability and control for human movement by resisting movement driven by the agonistic muscles. The role of antagonistic muscle activity during maximal isokinetic and isometric testing has been examined using electromyography (Bampouras et al., 2017; Kellis & Baltzopoulos, 1997; Kellis & Katis, 2007; Kubo et al., 2004; Saito et al., 2013). Kellis & Baltzopoulos, (1997) reported a significant contribution to resultant moment from the hamstring's antagonist activity during maximal isokinetic work, with larger antagonistic co-activation during concentric compared to eccentric actions. This can be explained by differences in moment and activation during concentric and eccentric loading, which suggest moment output per unit EMG activity is higher for eccentric work (Kellis & Baltzopoulos, 1998; Seger & Thorstensson, 2000). Muscle activation during isometric testing has also demonstrated differences in co-activation of the knee extensors with hip (Bampouras et al., 2017) and knee (Kubo et al., 2004) joint angle, which indicate increased antagonistic activation at longer muscle lengths.

Although co-activation serves as a protective mechanism during high muscle loading, strength training is expected to modulate the activation patterns of both agonistic and antagonistic muscles (Aagaard, 2003; Aagaard et al., 2002; Amiridis et al., 1996; Baroni et al., 2015; Hortobágyi & Katch, 1990; Westing et al., 1991a). Amiridis et al., (1996) reported reduced reciprocal inhibition in highly trained athletes during maximal voluntary eccentric contractions, resulting in only 12% antagonist co-activation compared to 38% in unskilled individuals. Thus, reduce antagonistic co-activation with training may serve to enhance force generation and increase maximum strength. Increased agonistic muscle activation and moment (voluntary and evoked) during knee extension have also been demonstrated on the stronger limb, which is indicative of training adaptations (Krishnan & Williams, 2009). Neural activation of the agonists accounted for 69% of the side-to-side differences; however, no side-to-side differences were observed in antagonistic muscle activity of the hamstrings.

2.3.3 Connective Tissue

2.3.3.1 Series Elastic Component

The SEC in Hill's (1938) muscle model represents the constituent parts of the muscle-tendon complex which are in series to the CC. They are responsible for force transmission to the skeleton as well as providing elastic properties that contribute to force output. The SEC consists partly of fibrous proteins, collagen and elastin, which influence the mechanical properties of the connective tissue. Collagen provides stiffness and tensile strength, but is unable to withstand compression forces, while elastin is compliant and very extensible. It is accepted that the tendinous tissues are responsible for the majority of series elasticity (Herbert & Crosbie, 1997; Morgan et al., 1978; Roberts, 2002), but elasticity of the cross-bridges, titin and Z-bands of the sarcomere also contribute (Herzog, 2019b; Huxley & Simmons, 1971; Linari et al., 1998; Lombardi & Piazzesi, 1990; Sugi & Tsuchiya, 1988).

In Hill's, (1938) investigation of the frog sartorius muscle, he suggested that the CC shortens at the expense of the SEC, which elongates under load during muscular contraction. This was later demonstrated using the sonomicrometry technique *in vivo*, whereby muscle fibres of the cat medial gastrocnemius shortened by 18-28% during ‘isometric’ contractions despite no changes in muscle-tendon unit length (Griffiths, 1991). Uncoupling between muscle and fascicle length changes, such that lengthening of the muscle-tendon complex occur simultaneously with fibre shortening and vice versa, further supports this notion (Hoffer et al., 1989). Lengthening of the SEC has also been suggested to reduce the metabolic cost of human movement, by allowing the CC to operate near its optimal length and velocity (Fukunaga et al., 2001; Lichtwark et al., 2007; Morgan et al., 1978; Muraoka et al., 2001; Roberts et al., 1997).

Various methods have been adopted to estimate mechanical properties of the SEC using isolated tendon specimens (Bennett et al., 1986; Butler et al., 1978; Cavagna, 1970; Harris et al., 1966; Jewell & Wilkie, 1958; Lieber et al., 1991; Walker et al., 1964; Wilkie, 1956); however, the SEC does not reside in a single region of the muscle-tendon complex and so its properties cannot be determined independently from the system**.** *In vitro* studies suggest the relationship between force and elongation (or stress-strain) of the SEC is initially curvilinear, indicating greater tendon compliance at low forces due to uncrimping of collagen fibres (Bennett et al., 1986; Butler et al., 1978; Cavagna, 1970; Jewell & Wilkie, 1958; Lieber et al., 1991; Rigby et al., 1959). Further increases in force begin to stretch the collagen fibres, resulting in a linear force-length relationship and constant stiffness of the SEC (Bennett et al., 1986; Butler et al., 1978; Cavagna, 1970; Jewell & Wilkie, 1958; Lieber et al., 1991; Rigby et al., 1959). Constant stiffness persists with increasing stress throughout the ‘elastic region’ until a plateau is reached (plastic region) at which deformation of the SEC is irreversible and rupture can occur (Butler et al., 1978; Partington & Wood, 1963; Viidik, 1968). Tensile testing of whole tendons commonly report ultimate stress between 50-100 MPa (Bennett et al., 1986; Butler et al., 1978) and strain at failure between 4-10% (Butler et al., 1978; Harris et al., 1966; Partington & Wood, 1963). However, compliance of the SEC, indicated by the gradient of the slope, varies greatly across various muscles and species due to differences in tendon length and thickness as well as material properties (Ker et al., 1988; Shadwick, 1990).

Tensile testing of preserved material *in vitro* has been criticised due to stress concentration and tissue slippage (Ker et al., 2000), alteration of properties due to tissue preparation and storage (Smith et al., 1996), and its poor representation of *in vivo* function (Zajac, 1989). Advances in ultrasound measurements have since made it possible to non-invasively measure the mechanical properties of intact tendons. Stress-strain relationships are commonly determined from maximal voluntary contractions, indicating maximum strains *in vivo* do not exceed the curvilinear ‘toe region’ (Hansen et al., 2006; Maganaris & Paul, 1999, 2000a). Maganaris & Paul, (1999) measured properties of the human tibialis anterior during isometric dorsiflexion and reported stress and strain values at maximum contraction intensity of 25 MPa and 2·5%, respectively. The patellar tendon also remains in the toe region during maximal voluntary contraction demonstrating lower strain values (< 10%; Hansen et al., 2006; Kubo et al., 2005) compared to *in vitro* studies (~15%; Butler et al., 1986; Johnson et al., 1994).Tendon strain during eccentric muscular contraction, however, is expected to increase above the ‘toe region’ and risks tendon rupture (Ker et al., 1988).

Adaptations in tendon mechanical properties have been demonstrated in response to training, inducing a leftward shift in stress-strain curves and increasing tendon stiffness and Young’s modulus (Hayashi, 1996; Kubo et al., 2001a; Reeves et al., 2003). The opposite is observed following periods of disuse as observed in the patellar tendon of individuals with spinal-cord injuries who demonstrated 77% lower tendon stiffness and 59 % lower Young’s modulus compared to able-bodied controls (Maganaris et al., 2006b). Ageing also influences tendon mechanical properties, with tendon stiffness 94% greater in adult men than in boys, and 84% greater in adult females then young girls (O’Brien et al., 2010) but a decline in tendon stiffness is observed with old age (Reeves, 2006). Older adults, who display a deterioration in tendon stiffness due to reduced collagen content, can, therefore, benefit from training interventions to mitigate age-related declines in physical function (Karamanidis et al., 2008; Maganaris et al., 2004; Reeves et al., 2003; Smith et al., 2024; Vogel, 1991).

Elastic properties of the SEC can accommodate cyclic movements, such as walking and running, through the storage and release of energy during the stretch-shortening cycle (Cavagna et al., 1964; Fukunaga et al., 2001; Ishikawa et al., 2005; Morgan et al., 1978). Direct measurements of the human gastrocnemius tendon *in vivo* suggests the tendon behaves like a spring during walking, contributing approximately 6% of the total external mechanical work (Maganaris & Paul, 2002) and thus, reducing muscular work and metabolic cost of locomotion (Cavagna et al., 1964; Fukunaga et al., 2001). Larger energy contributions are expected from more intensive exercise, such as sprinting and jumping (Bobbert, 2001; Böhm et al., 2006). Fukashiro et al., (1995) measured elastic energy stored in the Achilles tendon using a buckle-type transducer and found the tendon contributed 17-34% of the total calf muscle work during hopping/jumping. However, the capacity for storage and release of elastic energy is dependent on the tendons mechanical hysteresis which is subject- and region-specific (Kubo et al., 2001b, 2002; Maganaris & Paul, 2000b; Shadwick, 1990). Tendon stiffness also alters the joint moment-angle and moment-velocity properties, with stiffer tendons able to module CC length and shortening velocity to enhance force production (Kawakami et al., 2002; Wilson et al., 1994).

2.3.3.2 Parallel Elastic Component

The PEC is comprised of structures in-parallel to the CC that display elastic behaviour when the CC is not producing force and so, it functions independent of CC activation. The PEC is often associated with the connective tissues that surrounds the muscle and its compartments, as well as intrafibrillar proteins, such as the molecular spring 'titin' (Gillies & Lieber, 2011; Prado et al., 2005). The relationship between force and elongation of the PEC is described as highly nonlinear, with stiffness increasing slowly and then more rapidly as the muscle is lengthened beyond its slack state (Winter, 2009).

Force enhancement above isometric force following active stretch of the muscle has been observed in the muscle during activation (residual force enhancement; Abbott & Aubert, 1952; Edman et al., 1978; Morgan et al., 2000; Rassier et al., 2003) and also following deactivation (passive force enhancement; Herzog et al., 2003; Herzog & Leonard, 2002; Joumaa et al., 2007; Lee & Herzog, 2002; Rassier et al., 2003). The concept of sarcomere non-uniformity was initially proposed as a possible explanation for the force enhancement property (Morgan et al., 2000); however, many observations were left unexplained by the theory (Herzog, 2019a). Another more popular mechanism, involving the engagement of a passive structural element upon muscle activation, has since been proposed (Edman & Tsuchiya, 1996; Forcinito et al., 1998; Noble, 1992). Edman et al., (1978) first suggested that visco-elastic elements in parallel with the CC could account for the dependence of force enhancement on stretch magnitude but independence on stretch speed. This was later followed by theoretical and modelling descriptions of the potential role of a parallel elastic element in force enhancement following an active stretch of the muscle (Forcinito et al., 1998; Noble, 1992). Direct evidence has since been documented in isolated muscle preparations as well as intact muscles, with the calcium-sensitive, structural protein ‘titin’ identified as the main contributor (Herzog & Leonard, 2002; Joumaa et al., 2007; Lee & Herzog, 2002; Rassier et al., 2003). Passive force enhancement has been shown to occur primarily at long muscle lengths where passive forces naturally occur (Herzog & Leonard, 2002), is long lasting (> 25 s) (Herzog et al., 2003), increases with increasing stretch magnitudes and the amount of force during stretch (Herzog & Leonard, 2005), and is typically equal to or less than the total residual force enhancement (Herzog & Leonard, 2005).

2.3.4 Moment Arm Properties

The force-length relationship of isolated muscle states that the ability to produce maximal force is determined by its length. In the musculoskeletal system, changes in muscle length occur with changes in joint angle and so, the optimal muscle length corresponds to a joint angle where force production is maximal. Unlike the force-length relationship, however, moment-angle characteristics relate to the function of all muscles crossing a joint, which may differ in architecture and structure. The relationship between *in vivo* force-length and moment-angle properties is further complicated by the effect of moment arm length, such that the optimal angle may not coincide with the optimal muscle length (**Figure 2.8**; Hoy et al., 1990; Kellis & Blazevich, 2022).

Muscle moment is calculated as the muscle force multiplied by the perpendicular distance from the joint’s axis of rotation to the tendon line of action (muscle-tendon moment arm) running from origin to insertion. Resultantly, the contribution to joint moment from a muscle with a longer moment arm will be larger than a muscle with the same force producing capacity but with a shorter moment arm. As such, muscles with a smaller PCSA and thus, reduced force-producing capacity, may enhance joint moment in the presence of a larger moment arm. The active range of the muscle is also affected by changes in moment arm length, with a shorter moment arm enabling greater joint angular excursion for a given change in muscle length (Lieber & Fridén, 2000). Shorter moment arms, therefore, permit higher angular velocities over a larger operating range (Lieber & Fridén, 2000). Resultantly, the functional role of a muscle when considered as part of the intact musculoskeletal system, may not reflect its architectural characteristics as the change in muscle fibre length is highly dependent on the muscle-tendon moment arm.

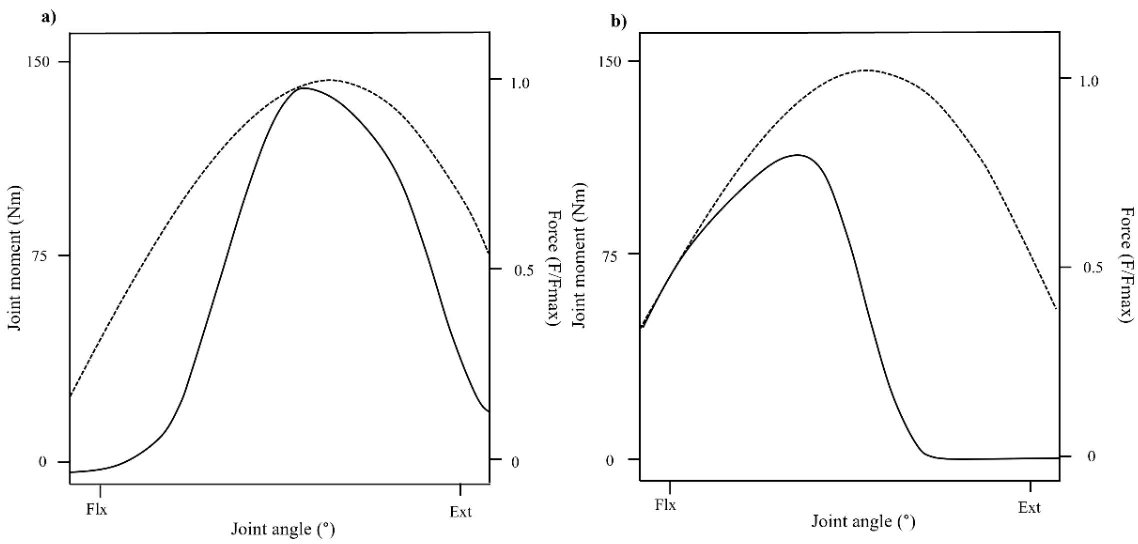

Figure 2.8 Effect of moment arm on isometric force- and moment-angle relationship (solid line) for the same biarticular muscle group at different lengths (a, b) due to changes in a secondary joint angle, where the dashed line represents a constant moment arm. The joint angle where isometric force peaks occurs near the joint angle where moment arm peaks in some configurations (a) but not in others (b; adapted from Hoy et al., 1990)

The effect of moment arm length on joint moment also explains paradoxical behaviour of antagonistic pairs (often referred to as Lombard's paradox) such as the quadriceps and hamstrings, which contract simultaneously during actions like the sit-to-stand, squatting and cycling (Andrews, 1987). Although the antagonistic muscle groups act in opposition (i.e., the quadriceps contribute to knee extension and hip flexion, and the hamstrings contribute to knee flexion and hip extension), the biarticular rectus femoris has a shorter moment arm at the hip than the biarticular hamstrings, but a longer moment arm at the knee, enabling simultaneous knee and hip extension due to larger extensor moments at each respective joint.

Muscle-tendon moment arms have been quantified using both direct and indirect methods, including tendon excursion measures on cadavers (An et al., 1981; Klein et al., 1996; Spoor et al., 1990; Visser et al., 1990), estimation from *in vivo* imaging techniques (Ito et al., 2000; Maganaris et al., 2006a; Tsaopoulos et al., 2007) and predictions from mathematical modelling (Menegaldo et al., 2004; Murray et al., 2002). Moment arms, in both cadavers and *in vivo*, have been shown to vary in a non-linear fashion as a function of joint angle (Kellis & Blazevich, 2022; Spoor et al., 1990; Tsaopoulos et al., 2006). For example, the moment arm of the patellar tendon generally decreases or follows an inverted-U path as the knee joint progresses from extension to flexion (Tsaopoulos et al., 2006). Contraction intensity has also been shown to influence moment arm by altering the position of the tendon relative to the joint axis (Maganaris et al., 1998a; Tsaopoulos et al., 2007); however, variable results exist between the tendon excursion and centre of rotation methods for moment arm calculation (Maganaris, 2004; Tsaopoulos et al., 2006). Musculoskeletal modelling of the lower limb has also demonstrated changes in moment arm lengths during maximum isometric contractions, with changes in quadriceps and hamstring moment arms resulting in altered peak torque magnitude and location (Hume et al., 2018).

2.4 Measures of Strength

Strength can be assessed using experimental and theoretical approaches to estimate the capacity of the musculature to produce force or moment under specified conditions (Conceição et al., 2012; Forrester et al., 2011; Ganeva et al., 2023; Heiden et al., 2009; King et al., 2012; Kozinc et al., 2021; Lewis et al., 2018; Maly et al., 2021; Pain et al., 2013). Both approaches can provide information about *in vivo* muscle function under isometric, concentric, or eccentric loading which may inform decision making related to performance enhancement and injury mitigation.

2.4.1 Experimental Approach

Various experimental methods exist for the assessment of muscular strength via measures of external forces acting within the system. Isokinetic dynamometry is considered the gold-standard method for measuring strength (maximal joint moment) and has widespread application for monitoring injury risk, rehabilitation and training (Bagordo et al., 2020; Brito et al., 2010; Brown & Whitehurst, 2003; Croisier et al., 2008; Douglas et al., 2017; Herbawi et al., 2022) yet, its feasibility in an applied environment is limited due to time and financial costs associated with data collection and analysis. As a result, field-based alternatives have become commonplace in both applied and research settings, providing a means to assess functional strength and performance outcomes (Bazyler et al., 2015; Bily et al., 2019; Ceroni et al., 2012; Gonzalo-Skok et al., 2015; Impellizzeri et al., 2007; Madruga-Parera et al., 2021; McMahon et al., 2015; Sannicandro et al., 2011).

2.4.1.1 Isokinetic Dynamometers

Muscle function is often assessed on an isokinetic dynamometer under isometric or isovelocity conditions, with both modes offering a safe and controlled environment for maximal effort testing (Baltzopoulos, 2017). Dynamometers are widely available and as such, a wealth of data exists on strength characteristics, including torque-angle and torque-velocity properties, particularly at the knee joint (Alcazar et al., 2023; Caldwell et al., 1993; Delextrat et al., 2020; Froese & Houston, 1985; Ganeva et al., 2023; Harries & Bassey, 1990; Lanza et al., 2003; Pain et al., 2013; Pincivero et al., 2004; Westing et al., 1988).

A resistive moment is applied by the dynamometer to ensure constant loading or angular velocity, where the resistive moment is equal to the applied moment during constant velocity (acceleration = 0 $m \cdot s^{-1}$) of the input arm. To determine the actual joint moment exerted by the muscles, the resistive moment must be subtracted from the net moment, and the gravitational moment corrected for. The gravitational moment, resulting from the weight of the limb and the dynamometer attachments, is maximum with the limb in the horizontal position (0° crank angle) and equal to zero with the segment in the vertical position (90° crank angle). Correction of the gravitational moment can be achieved using the automated correction feature within the dynamometer software. The maximum gravitational moment (at horizontal) is often used to adjust the measured moment by either adding or subtracting its value depending on whether the limb is being resisted (add) or assisted (subtract) by gravity. However, the effect of passive structures on joint moment varies with joint angle due to changes in passive force with elongation (Moo et al., 2020), which should be considered when correcting for gravitational effects using a single measurement position where passive force may be excessive. Passive torques due to the elastic properties of neighbouring soft tissues can also be accounted for by measuring passive torque while the dynamometer moves the limb throughout the joint range of motion. Passive torque measures at tested crank angles can then be accounted for, leaving the active torque exerted by the contractile elements.

The dynamometer moment, once corrected for gravitational and inertial effects, represents the two-dimensional rotation of the input arm about the dynamometer crank axis (Kaufman et al., 1995) which is a product of the all the agonistic and antagonistic muscles and connective structures exerting force at the joint. It is necessary for the crank axis and joint axis to be aligned to make accurate measurements of the applied moment. However, axes misalignment during maximal voluntary contractions (MVC) can be large (Arampatzis et al., 2004, 2005; Kaufman et al., 1995), particularly when the orientation of the joint action and the dynamometer allow for greater displacement of the joint and near the optimal joint angle when the applied moment is larger. Standardised protocols are required to minimise such errors, including alignment of the axes during submaximal or maximal loading near to the expected optimal joint angle, as well as accurate subject positioning and adequate joint/segment stabilisation (Baltzopoulos, 2017). To further reduce measurement error due to axes misalignment, the joint angle may be corrected using kinematic measures via goniometry (Conceição et al., 2012; Forrester et al., 2011) or motion capture techniques (King et al., 2012; Lewis et al., 2018).

Maximum strength is often measured during MVC as instantaneous peak torque or average peak torque (during prolonged isometric contractions; Abourezk et al., 2017; Barrué-Belou et al., 2024; Čeklić & Šarabon, 2021; Ganeva et al., 2023; Lisee et al., 2019; Zwolski et al., 2016). During isometric testing, active tension is developed within the muscle but changes in joint angle are restricted by the dynamometer. Isokinetic testing, on the other hand, enables rotation of the limb about the axis of rotation, such that dynamic muscular contractions can be assessed under constant angular velocities. Although both types of testing offer a safe and controlled environment for testing, isokinetic protocols require adequate familiarisation due to the task novelty and complexity (Dirnberger et al., 2012; Nugent et al., 2015). The risk of injury during isokinetic work should also be considered, particularly at high eccentric velocities where moment potential is increased and in subjects who are injured or unfamiliar to the testing protocol.

2.4.1.2 Force Platforms

Functional strength can be assessed using force platforms, with isometric and dynamic testing commonly used to assess performance and injury risk from closed kinetic chain, multi-joint tasks (Bailey et al., 2013; Brumitt et al., 2020; Fort-Vanmeerhaeghe et al., 2019, 2022; Guan et al., 2022; Lisee et al., 2019; MacSweeney et al., 2023, 2023). Commercially available force platforms typically consist of a rectangular steel plate supported by piezo-electric or strain-gauge force transducers which are capable of measuring ground reaction forces in up to three directions (longitudinal, medio-lateral and anterior-posterior). Multiaxial force plates (measuring in multiple axes) are commonly used in research to assess ground reaction forces during human movement and performance; however, uniaxial force plates (measuring in one axis) provide a cheaper option for collecting vertical ground reaction force data. When used in a twin-system, force plates also provide additional diagnostic capabilities, allowing for the assessment of inter-limb differences during bilateral tasks (Dai et al., 2019; Pérez-Castilla et al., 2021) which is not possible using isokinetic dynamometry.

Multi-joint isometric strength tasks, such as the isometric midthigh pull (IMTP), have become common for the assessment of force generation (e.g., peak force) as they are perceived as less fatiguing and safer compared to repetition maximum strength testing (Comfort et al., 2019; De Witt et al., 2016). The IMTP has also shown high reliability both within and between sessions, as well as low measurement error and variability (Beckham et al., 2018; Comfort et al., 2014; De Witt et al., 2016; Dos'Santos et al., 2017d, 2018b; Haff et al., 2015). However, the task requires some familiarisation to ensure proper technique and standardised procedures must be followed to allow for accurate processing of kinetic variables (Comfort et al., 2019). For instance, variability in kinetic outcomes has been observed in relation to different knee, hip and trunk angles during the IMTP (Comfort et al., 2014; Dos'Santos et al., 2017d). Recommended testing procedures have been described which advise the use of externally focussed verbal cues, strong encouragement throughout the task, and familiarisation during submaximal and maximal trials (Comfort et al., 2019). Standardised positioning should also be adopted, including minimal pre-tension before the pull, an upright torso with the bar in contact with the thighs and close to the inguinal crease, attachment to the bar by lifting straps or hooks and joint angles of 125-145° and 140-150° at the knee and hip, respectively (where full joint extension corresponds to 180°; Comfort et al., 2019). When adopting a mid-bar position (as described above), the IMTP can be considered a test of knee extensor and ankle plantarflexor strength as the musculature operates closer to their relative maximum capacity (Ahn et al., 2021). Comparatively, there is a greater demand on the posterior chain muscles when a low-bar position (neutral spine, but greater hip flexion) is adopted (Beckham et al., 2018).

Multi-joint dynamic tasks, such as jumping and hopping, are also frequently used to assess neuromuscular function in applied practice, with the integration of force plates allowing for in-depth kinetic analyses (Cormie et al., 2008, 2009; Laffaye et al., 2014; McMahon et al., 2017c, 2017b). Jump testing is quick to perform, requires minimal familiarisation, and has high ecological validity compared to single-joint maximal effort testing (Moir et al., 2005; Nibali et al., 2015). However, reliability between and within sessions demonstrate test and metric sensitivity such that some methods may not provide meaningful results (González-García et al., 2024; Merrigan et al., 2020; Pérez-Castilla et al., 2021). Performance-based measures, such as height and distance, which do not necessarily require the use of a force plate, also provide a simple and widely affordable tool for athlete monitoring (Bishop et al., 2021c, 2022c; Fort-Vanmeerhaeghe et al., 2021; Williams et al., 2011) but may not provide adequate information about muscle function and jump strategy. The knee joint is one of the main contributors to performance, with strong correlations identified between knee extensor strength and vertical and horizontal jumping (Iossifidou et al., 2005; Kotsifaki et al., 2021; Tsiokanos et al., 2002a). However, biarticular muscles enable transfer of energy throughout the lower limb (Jacobs et al., 1996; Prilutsky & Zatsiorsky, 1994), and the relative contribution from the hip, knee and ankle has been shown to vary between vertical and horizontal tests (Kotsifaki et al., 2021).

2.4.2 Theoretical Approach

Modelling techniques have been used more recently to provide insight into the behaviour of skeletal muscle in human movement using mathematical relationships (Conceição et al., 2012; Heinen et al., 2019; King et al., 2012; Lewis et al., 2018; Wilson et al., 2006). Such approaches allow for the controlled investigation of a single variable's effect on the system and can eliminate unavoidable measurement errors in a simple representation of reality. Modelling techniques are also essential in forward dynamics simulation models to better understand movement for prediction and improvement of performance outcomes (Wilson, King & Yeadon, 2006; Yoshioka et al., 2010).

In accordance with the mechanical properties of skeletal muscle, muscle models generally express muscle force as a function of length, velocity and neural activation. Lumped muscle models or joint actuators (where net torque is modelled as the sum of all muscle moments at the joint) do not account for the behaviour of individual muscles but have been shown to demonstrate sufficient complexity for simulations of optimal jumping (Alexander, 1990). Subject-specific strength parameters can also be easily modelled from torque measurements collected via isokinetic dynamometry (Conceição et al., 2012; Forrester et al., 2011; King et al., 2012; Lewis et al., 2018, 2021; Yeadon et al., 2006); however, there is no consensus in the literature on an optimal measurement protocol for isometric or isovelocity testing.

Search algorithms are utilised to find optimal strength parameters from experimental data by minimising or maximising a cost function. The likelihood of convergence on the global optimum is determined by the choice of optimisation algorithm (Corana et al., 1987) and the cost function to be minimised (Erdemir et al., 2007) which is important when attempting to find an optimal solution for human performance. Traditional optimisation techniques, such as gradient descent, can struggle with the complex landscapes characterized by multiple local minima and large parameter spaces (Van Soest & Casius, 2003). Simulated annealing, however, is an example of a heuristic search algorithm that is able to avoid being trapped in local minima by retaining information about the entire search space and learning from past solutions in a probabilistic manner (Corana et al., 1987; Van Soest & Casius, 2003). The method models the physical process of annealing in metallurgy which involves heating and then controlled cooling of a material to alter its physical properties. Accordingly, simulated annealing begins with an initial estimate and a high 'temperature' that allows the algorithm to extensively explore the solution space. The temperature gradually decreases according to a cooling schedule. At each step, a new solution is proposed by making a small random change to the current solution. The acceptance of this new solution is probabilistically determined based on the difference in the objective function and the current temperature. By accepting potentially "bad" moves that increase the objective function, simulated annealing can escape local minima and continues to search for better solutions. The probability of accepting worse solutions decreases as temperature lowers until the algorithm converges at an optimal solution. This method has previously been used to determine strength parameters for isometric and isovelocity relationships as well as series elastic and neural activation properties for a variety of forward dynamic simulation models for human movement (McErlain-Naylor et al., 2021).

Performance of the search algorithm is affected by the nature and complexity of the problem and so, should be appropriately considered. Specifically, the optimal solution can vary as a result of the cost function and the weighting of its components which should be tailored to the problem in question (Erdemir et al., 2007). Both weighted and unweighted root mean square (RMS) differences between input and output have been used previously to assess model performance in the muscle modelling literature (Forrester et al., 2011; King et al., 2012). Unweighted cost functions are useful when experimental data is expected to be close to optimal, whereas weighted functions can be used to influence the prediction of values by weighting some components higher than others. For instance, an unweighted RMS difference has been shown to reproduce isometric torque data better than a weighted RMS difference (Forrester et al., 2011). Alternatively, a weighted cost function better represented isovelocity data, resulting in the majority of points lying beneath the fitted profile (Forrester et al., 2011).

2.5 Summary

The mechanical, physical and neuromuscular properties of the muscle-tendon complex have been detailed in relation to their effect on muscle function and performance. Both experimental and computational methodological approaches have also been reviewed, with their utility for the *in vivo* assessment of maximum and functional strength discussed. These concepts and techniques must be properly understood to ensure appropriate assessment of muscular strength and subsequently, inter-limb asymmetries in strength-based metrics. The following chapter will provide an in-depth review of the literature on inter-limb differences in strength, with a particular focus on methods of assessment, and calculation and interpretation of asymmetry scores across various populations.

Chapter 3: Systematic Review on the Calculation, Thresholds and Reporting of Inter-Limb Strength Asymmetry

3.1 Chapter Overview

This chapter discusses the results of a systematic review of the literature on inter-limb asymmetries in maximum and functional strength, which aimed to answer methodological questions regarding the measurement and calculation of between-limb asymmetries in strength-based metrics. As the quantification of asymmetry initially relies on the assessment of muscular strength itself, this chapter firstly summarises the numerous tests and metrics used to measure both isolated and functional strength, for the calculation of asymmetry. Asymmetry indexes adopted within the literature to calculate differences in strength between limbs are also identified and their appropriateness for calculating asymmetry is critically discussed. Furthermore, the thresholds applied to interpret asymmetry scores are reviewed and interrogated in relation to the evidence base for their use. Finally, a detailed summary of normative values for inter-limb asymmetries in strength is provided and associations with injury and performance amongst various populations are explored.

3.2 Introduction

Inter-limb asymmetry, defined as a lack of equality between limbs or muscle groups, has been the topic of interest for various studies over recent years, particularly in strength and conditioning literature, due its association with increased injury risk and weaker performance (Bishop et al., 2019a, 2019b, 2021b; Brumitt et al., 2020; Fort-Vanmeerhaeghe et al., 2020, 2022; MacSweeney et al., 2023; Madruga-Parera et al., 2020, 2021; Steidl-Müller et al., 2018). Asymmetries between limbs may result from chronic loading to one side of the body (Hart et al., 2016), where limb preference or sport-specific requirements may be evident (Bishop et al., 2019d, 2019b, 2021b). Inter-limb asymmetries in maximum and functional strength have been investigated in a range of populations to better understand the prevalence and potential consequences of strength asymmetry, with asymmetries of 10-15% or more often considered problematic (Barber et al., 1992; Kyritsis et al., 2016; Rohman et al., 2015). As such, training interventions have been recommended in an attempt to reduce imbalances and improve symmetry between limbs (Bettariga et al., 2022). However, a more recent perspective questions the use of pre-determined thresholds due to the specific nature of asymmetry, such that variability in scores is observed between tests, metrics and populations (Bishop et al., 2019c, 2019b; Dos'Santos et al., 2017c; Read et al., 2021). Instead, an individual approach to asymmetry has been proposed, which considers sample-specific thresholds and individual variability (Bishop, 2021; Dos'Santos et al., 2021). Some researchers also highlight that asymmetry of some degree is inevitable and can play a functional role in human development, movement and performance (Afonso et al., 2022).

The literature has reported varying magnitudes of inter-limb strength asymmetry, from close to perfect symmetry to asymmetries larger than 15% across sexes, age groups, activity levels and injury status (Ceroni et al., 2012; Dai et al., 2019; Eitzen et al., 2010; Hoogeslag et al., 2019; Jones & Bampouras, 2010; Laroche et al., 2012; Leister et al., 2018; O'Malley et al., 2018; Ruas et al., 2015). Some evidence suggests that larger imbalances in strength are associated with weaker performance in jumping, sprinting, change of direction and sport-specific tasks (Bell et al., 2014; Bishop et al., 2018c, 2021b; Kons et al., 2023; Madruga-Parera et al., 2021; Michailidis et al., 2020), which could result from altered movement mechanics (Abourezk et al., 2017; Thomas et al., 2020). Strength differences between limbs have also been associated with an increased risk of prospective injury (Brumitt et al., 2013; Croisier et al., 2008; Fort-Vanmeerhaeghe et al., 2022), which suggests action should be taken to reduce inter-limb imbalances. However, longitudinal data suggest asymmetries may not track over time (Bishop et al., 2022c) and conflicting evidence indicates strength asymmetry may not always cause dysfunction (Dos'Santos et al., 2018c; Işın et al., 2022; Lockie et al., 2014; Opar et al., 2015). Furthermore, larger asymmetries measured in higher division soccer players than lower division players, suggests competitive level may influence strength asymmetry (Ferreira et al., 2018) and asymmetry may even be associated with superior performance (Pleša et al., 2022). Therefore, the relationship between inter-limb asymmetry and injury and performance remains unclear and requires further investigation.

Various methodological approaches have been adopted for the assessment of inter-limb asymmetry in maximum and functional strength. The isokinetic dynamometer is commonly used as it is considered the gold-standard for measuring maximum strength due to its high reliability when measuring isometric and isokinetic peak torque *in vivo* (Maffiuletti et al., 2007; Tsiros et al., 2011). However, expensive experimental set-ups and lengthy protocols are generally unfeasible in a field-based setting. Furthermore, poor reporting and standardisation of appropriate dynamometer testing protocols poses further challenges when assessing asymmetries in strength (Baltzopoulos et al., 2012). Functional performance tests, including various jumping and hopping tests (Bishop et al., 2017) that can be assessed using cost-effective measuring devices (Comyns et al., 2023), have been proposed as valid and reliable field-based alternatives to single-joint strength measurements performed on an isokinetic dynamometer (Impellizzeri et al., 2007; Maulder & Cronin, 2005). However, some evidence suggests that the asymmetries determined from field-based tests have limited between-session reliability, despite good reliability in unilateral performance variables between sessions (Pérez-Castilla et al., 2021). This study also demonstrates task and metric sensitivity, as well as inconsistencies in the magnitude and direction of asymmetries measured one week apart. Research investigating the direction of asymmetry between-sessions using kappa coefficients similarly demonstrates inconsistencies between sessions, tests and metrics, which reinforces the notion that asymmetry is highly variable (Bishop et al., 2020a; Cuthbert et al., 2021; Pérez-Castilla et al., 2021). Task and metric sensitivity may be overcome by implementing a battery of tests. However, practitioners should also consider test-retest reliability of asymmetry scores and directional consistency across repeated measures before classifying an individual's asymmetry profile.

Methodological differences also exist in the calculation of asymmetry scores, with numerous indexes reported in the literature. Often, asymmetries are calculated as a percentage, where one limb is normalised to the reference limb (Ceroni et al., 2012; Eitzen et al., 2010; Leister et al., 2018; Palmieri-Smith & Lepley, 2015; Schmitt et al., 2015); however, some indexes divide the absolute difference between limb values by the value of the desirable limb (Impellizzeri et al., 2007; Jones & Bampouras, 2010; Laroche et al., 2012). Both approaches require a distinction between limbs, such as injured/uninjured, right/left and dominant/nondominant, where one limb is assumed to be the stronger or better performing of the two limbs. Alternatively, the numerator can be divided by a statistic derived from both limb values such as the mean, sum of, minimum or maximum value (Bailey et al., 2015; Bell et al., 2014; Dai et al., 2019). However, there are limitations associated with selecting a reference limb or value, which can lead to inflated scores and different values of asymmetry depending on which limb is stronger (Bishop et al., 2016). Furthermore, the lack of standardisation limits comparison between studies which adopt different asymmetry indexes, with variability in scores expected due to inherently different numerical derivation. It should also be noted that the literature includes references to both symmetry and asymmetry, which requires the reader to be observant of opposite terminologies. However, this poses less of a challenge for data comparison than using different input variables and mathematical processes. This is because 0% asymmetry is equivalent to 100% symmetry, which marks the absence of asymmetry and therefore, complete symmetry.

Despite widespread assessment of inter-limb asymmetry, no standard practice exists for the interpretation of scores. Although many studies have adopted a threshold of between 10-15% to identify abnormal differences between limbs (Croisier et al., 2002; Ebert et al., 2018; Kyritsis et al., 2016; Rohman et al., 2015; Ruas et al., 2015; Schmitt et al., 2015), inconsistent findings undermine the use of pre-determined thresholds in the identification of meaningful asymmetry between limbs. Thus, it is crucial to ensure interpretation of inter-limb strength asymmetry is based upon original evidence and draws upon appropriate methodological practices. This would enable researchers and practitioners to distinguish between asymmetries that are problematic from those that may serve a functional purpose in human movement and performance. Therefore, the aims of this systematic review were to: 1) assess the appropriateness of existing quantitative methods for the calculation of asymmetry, 2) interrogate the evidence basis for literature reported thresholds used to define asymmetry and 3) summarise normative levels of inter-limb strength asymmetry and their effects on injury and performance.

3.3 Methods

The systematic review was designed according to PRISMA guidelines (Liberati et al., 2009; Moher et al., 2009, 2015).

3.3.1 Search Strategy

Articles were retrieved from the following databases: PubMed, Scopus, SPORTDiscus with Full Text and Web of Science.

The search process (**Figure 3.1**) was divided into two stages to capture all relevant articles. Both stages were designed to retrieve articles that clearly addressed the methods associated with measuring strength asymmetry, including isolated strength, functional performance and power, to ensure appropriate understanding and comparison of methodologies could be made. For stage one, the search strategy was designed to exclude participants with neurological disorders due to their potential influence on asymmetry methodology and outcomes.

Search terms and combinations for stage one were informed by existing literature and included:

1. (Asymmetr* OR Symmetr* OR Imbalance* OR "Side to side" OR "Limb dominance" OR "Leg dominance" OR "Limb preference" OR "Leg preference")
2. AND (Calculat* OR Measur* OR Reliability OR Reproducibility OR Validity OR Accuracy OR Effectiveness OR Repeatability OR Equations OR Formula*)
3. AND (Strength OR Power)
4. NOT (Patholog* OR Disorder OR Disease OR Dysfunction OR Syndrome OR Spastic* OR Defect OR Disability OR Ataxia OR Chorea OR Dystonia OR "Multiple system atrophy" OR Myoclonus OR "Progressive supranuclear palsy" OR "Restless legs" OR Tourette* OR Tic OR Tremor* OR "Multiple Schlerosis" OR Stroke OR Epilepsy)

Stage two was designed to ensure articles investigating individuals with lower body disability, but an absence of disease or neurological injury, could be identified as these articles were likely to be excluded from stage one results due to the fourth string of search terms. The upper body function of wheelchair users may be considered normal or high functioning. As such, articles retrieved from stage two were expected to offer additional insight into methodologies associated with strength, power or functional performance asymmetry that might otherwise be missed by the search terms of stage one.

Search terms for stage two were informed by existing literature and included:

1. (Asymmetr* OR Symmetr* OR Imbalance* OR "Side to side" OR "Limb dominance" OR "Leg dominance" OR "Limb preference" OR "Leg preference")
2. AND (Calculat* OR Measur* OR Reliability OR Reproducibility OR Validity OR Accuracy OR Effectiveness OR Repeatability OR Equations OR Formula*)
3. AND (Strength OR Power)
4. AND (Wheelchair*)

Additional searches were conducted in Google Scholar and an institutional library database in an attempt to retrieve full-text articles if they were not available via the aforementioned databases. Searches were conducted between January and March 2020. Reference lists of the included full-text articles were also screened for relevant articles investigating strength, power or functional performance asymmetry that were not identified by initial searches.

3.3.2 Screening and Eligibility Criteria

Restrictions were applied to limit the searches to journal articles, available in English. Database searches were limited to articles available in full text, investigating human participants, and published in sport and exercise science related journals where possible. No further limiters were applied to ensure a wide scope for the review. Identified articles were exported to the referencing software, Mendeley, where duplicates were removed. The title and abstract of retrieved articles were screened to exclude articles unrelated to sport and exercise science and articles not available in full text. The remaining full-text articles were then screened for eligibility and only included if they met the inclusion criteria. Inclusion criteria required articles to be original journal articles, available in English and involving living human participants without disease or a neurological condition/injury. Articles were required to investigate inter-limb strength asymmetry and provide comprehensive detail of the measurement methods and asymmetry index calculation to allow for a critical examination of the study results.

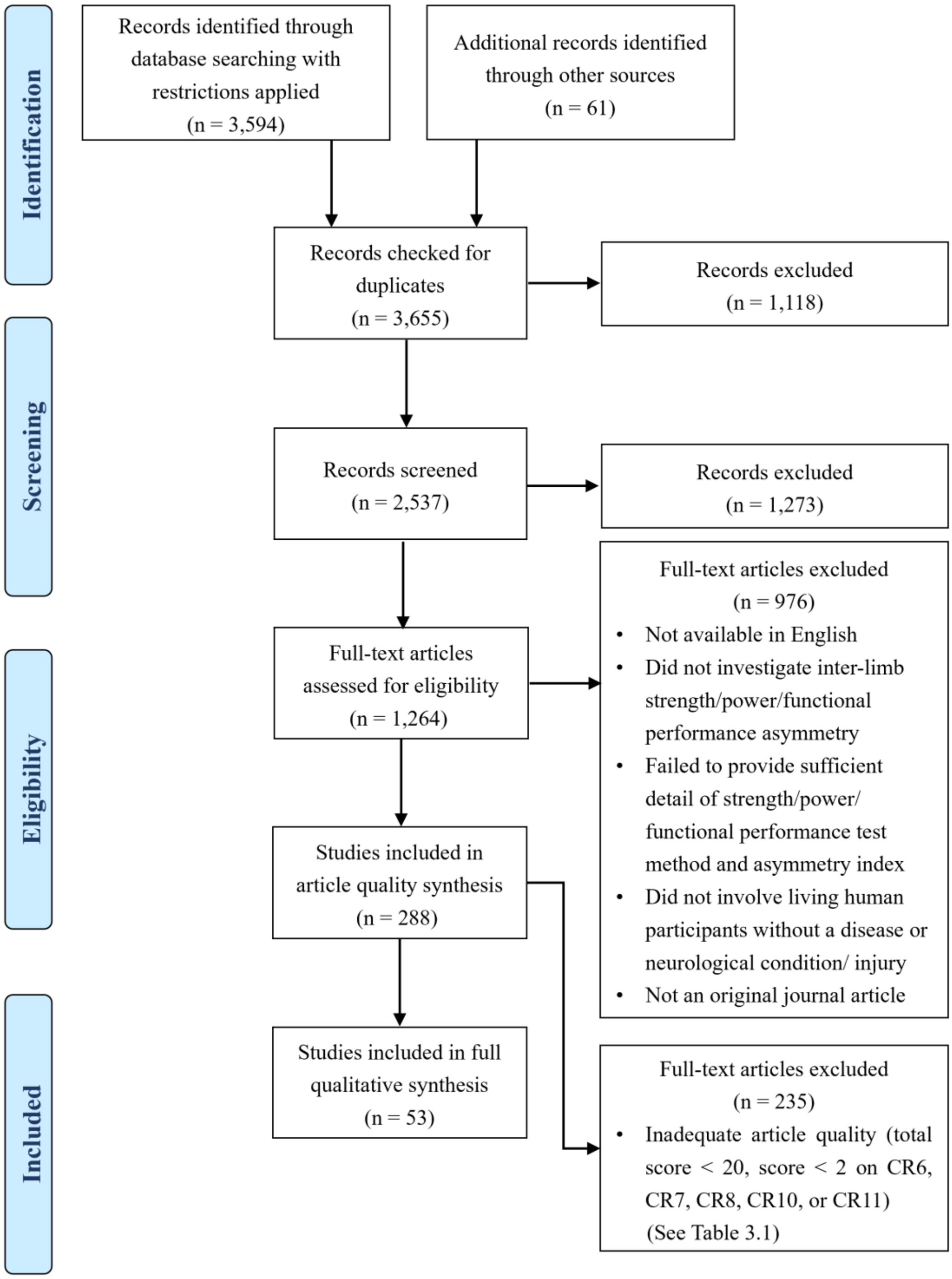

Figure 3.1 Flow diagram showing the identification and selection of the articles for this review

3.3.3 Risk of Bias

A sample (*n* = 252, approximately 10%) of the articles retrieved from the initial searches after removing duplicates were independently screened for eligibility (excluding article quality) by a primary and secondary reviewer. Upon consistent agreement between reviewers, the remaining articles were screened by the primary reviewer only. The secondary reviewer was responsible for monitoring this process to reduce the risk of bias. Where disputes arose, decisions were settled through discussion between both reviewers. Article quality was assessed in accordance with the screening protocol already stated, where a sample (*n* = 28, approximately 10%) was assessed for agreement before the remaining articles were screened.

3.3.4 Article Quality Assessment

Article quality was assessed using a modified version of a previously developed scale, established for use in systematic reviews (Peters et al., 2010). The scale was modified to ensure a critical appraisal of the current review's aims relating to strength and strength asymmetry testing (**Figure 3.1**). The scale evaluated article quality based on twelve criteria, which were each scored on a scale between 0-2 (where 2 = Yes, 1 = Lacks Detail and 0 = No). Summation across all criteria provided a total score, expressed as a percentage. To enhance the quality of this review, articles were required to reach a total score of 20/24 (83%). This equates to a score of 0 for up to two of the criteria or a score of 1 for up to four of the criteria. As thresholds used to identify 'high quality' articles vary in the literature (Ceyssens et al., 2019; Nugent et al., 2021; Peters et al., 2010), the 83% threshold used for the current review was devised based upon individual scores achieved across all twelve criteria, with the aim of including only the highest quality research. Articles were also required to score 2/2 on 5 of the 12 criteria which specifically addressed the study protocol (CR6), outcome variables (CR7), test method (CR8), asymmetry index (CR10) and results (CR11) as complete scores in these areas were necessary to provide the information required to satisfy the aims of the review.

Table 3.1 Article Quality Assessment Tool (adapted from Peters et al., 2010)

Criterion
CR1. Are the research objectives or aims clearly stated?
CR2. Is the study design clearly described?
CR3. Is the sample size used justified?
CR4. Are inclusion/exclusion criteria clearly stated?
CR5. Are appropriate subject information and anthropometric details provided?
CR6. Is the strength/power/functional performance asymmetry protocol properly described?
CR7. Are the variables used to measure strength/power/functional performance properly defined in the introduction or methods section?
CR8. Are the tests used to measure strength/power/functional performance properly described?
CR9. Are the instruments/measurements used to measure strength/power/functional performance validated for strength measurements (previously trialled, piloted or published)?
CR10. Is an inter/between-limb strength/power/functional performance asymmetry calculation provided or referenced appropriately?
CR11. Are the main outcomes of the study relating to strength/power/functional performance asymmetry clearly reported?
CR12. Are the limitations of the study clearly described?

N.B Each criterion was scored as follows, 2 = Yes; 1 = Limited Detail; 0 = No

3.3.5 Data Extraction

For this review, the term 'strength' was used to describe any strength-based assessment including maximum and functional strength tests and power tests. The following data were extracted from each source using data extraction forms developed *a priori*: (1) study design, (2) sample characteristics, (3) inclusion/exclusion criteria, (4) strength asymmetry test, (5) strength calculation/index, (6) strength asymmetry threshold, (7) comparators (8) outcome measures, (9) intervention, (10) follow-up and (11) main findings. An extracted data table of sample characteristics, tests and outcome variables was constructed as applicable to this review (**Figure 3.2**).

3.3.6 Data Synthesis

The extracted data was used to explore literature features related to population-specific characteristics, testing methods, calculations and asymmetry thresholds. To examine the robustness of asymmetry calculations, a quantitative analysis of the asymmetry indexes was performed using hypothetical scores for three separate scenarios: 1) symmetry, where limb A = B, 2) asymmetry, where limb A > B and 3) asymmetry, where limb A < B (Appendix 1, **Table A1.1**).

Where an asymmetry threshold was applied in the methodology of the study, the evidence base for the stated threshold was traced retrospectively. The evidence base was further examined to explore whether the study identified the origin of the evidence, where the stated threshold was based on original data examined in the study itself.

Where the included article itself was not the origin of the evidence, the references provided to support its use were identified and assessed (direct citations). Where the direct citations failed to provide the origin of the evidence, references provided by the direct citations were identified and assessed (indirect citations). The evidence base for the stated threshold in the study was categorised according to the following Tier system, where the included article:

Tier 1: Provided the origin of the evidence for the threshold
Tier 2: Directly cited the origin of the evidence
Tier 3: Indirectly cited the origin of the evidence
Tier 4: Failed to provide or cite the origin of the evidence

Included articles that provided either Tier 1 or 2 evidence were considered to be more reputable because the origin of the threshold was based upon original findings from the included article or its direct citations. However, it should be noted that interrogation of the research quality for each evidence source was beyond the scope of this review.

Table 3.2 Summary of sample demographics and methods used to measure inter-limb strength asymmetry in the included articles ($N = 53$)

			Sample Characteristics								**Strength Asymmetry Test**									**Sample Characteristics**									
											Isolated				**Functional**														
	Quality Score	**Total Sample Size (N)**	Male	Female	Injured/Post-Surgery	Uninjured	Athlete	Non-Athlete	Young (≤ 55 yrs.)	Old (> 55 yrs.)	Isokinetic Dynamometer	Stabilised Dynamometer	Hand-Held Dynamometer	Weight-Training Machine	Multi-Joint Strength Test	Nordic Hamstring	Jumping/Hopping	Push-Up	Seated Shot-Put	Torque	Force	Power	Impulse	Jump/Hop Height	Jump/Hop/Throw Distance	Vertical GRF	1-Repetition Maximum	Work Done	Rate of Force Development
Abourezk et al., (2017)	22	36	✓	✓	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Ageberg & Roos, (2016)	23	54	✓	✓	✓	-	-	✓	✓	-	-	-	-	✓	-	-	✓	-	-	-	-	✓	-	✓	✓	-	-	-	-
Almeida et al., (2019)	24	70	✓	✓	✓	-	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Ardern et al., (2015)	21	42	✓	-	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Batty et al., (2019)	22	100	✓	✓	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Benjanuvatra et al., (2013)	20	58	✓	✓	-	✓	-	✓	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	✓	✓	-	✓	-	-	-
Bishop et al., (2019c)	20	28	?	?	-	✓	✓	-	✓	-	-	-	-	-	✓	-	✓	-	-	-	✓	-	✓	✓	-	-	-	-	-
Bishop et al., (2019d)	21	16	-	✓	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	-	-	-	-	-
Bookbinder et al., (2020)	23	52	✓	✓	✓	✓	-	✓	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	-	-	-
Bourne et al., (2015)	22	178	✓	-	✓	✓	✓	-	✓	-	-	-	-	-	-	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-
Carabello et al., (2010)	23	93	✓	✓	-	✓	-	✓	✓	✓	-	-	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	✓	-	-
Chmielewski et al., (2014)	20	125	✓	✓	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	✓	-	-	-	-
Clark & Mullally, (2019)	23	23	-	✓	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	-	-	-
Coratella et al., (2018)	24	27	✓	-	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Costa Silva et al., (2015)	20	22	?	?	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Dai et al., (2019)	23	499	✓	✓	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	✓	-	-	✓	-	-	✓	-	-	-	-	-

Table 3.2 Summary of sample demographics and methods used to measure inter-limb strength asymmetry in the included articles (*N* = 53) ***continued***

			Sample Characteristics								Strength Asymmetry Test									Sample Characteristics									
											Isolated					Functional													
	Quality Score	**Total Sample Size (N)**	Male	Female	Injured/Post-Surgery	Uninjured	Athlete	Non-Athlete	Young (≤ 55 yrs.)	Old (> 55 yrs.)	Isokinetic Dynamometer	Stabilised Dynamometer	Hand-Held Dynamometer	Weight-Training Machine	Multi-Joint Strength Test	Nordic Hamstring	Jumping/Hopping	Push-Up	Seated Shot-Put	Torque	Force	Power	Impulse	Jump/Hop Height	Jump/Hop/Throw Distance	Vertical GRF	1-Repetition Maximum	Work Done	Rate of Force Development
de Lira et al., (2017)	21	112	✓	-	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Dos'Santos et al., (2017b)	23	22	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-
Dos'Santos et al., (2018c)	22	20	✓	-	-	✓	✓	-	✓	-	-	-	-	-	✓	-	-	-	-	-	✓	-	✓	-	-	-	-	-	-
Fältström et al., (2017)	24	154	-	✓	✓	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-
Fort-Vanmeerhaeghe et al., (2015)	21	29	-	✓	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	-	-	-
Fort-Vanmeerhaeghe et al., (2016)	20	79	✓	✓	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	-	-	-	-	-
Guney-Deniz et al., (2020)	24	87	✓	✓	✓	✓	-	✓	✓	-	✓	-	-	-	-	-	✓	-	-	✓	-	-	-	-	✓	-	-	-	-
Hadzic et al., (2014)	20	183	✓	✓	✓	✓	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Harput et al., (2018)	22	72	✓	-	✓	-	-	✓	✓	-	✓	-	-	-	-	-	✓	-	-	✓	-	-	-	-	✓	-	-	-	-
Hart et al., (2014)	20	31	✓	-	-	✓	✓	-	✓	-	-	-	-	-	✓	-	-	-	-	-	✓	-	-	-	-	-	-	-	-
Hiemstra et al., (2008)	23	48	✓	✓	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Holsgaard-Larsen et al., (2014)	24	48	✓	-	✓	✓	-	✓	✓	-	-	✓	-	-	-	-	✓	-	-	✓	-	-	-	✓	✓	-	-	-	-
Hubbard et al., (2007)	23	60	✓	✓	✓	✓	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	✓	✓	✓	-	-	-	-	-	-	-
Hughes et al., (2019)	21	125	✓	✓	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Kaminska et al., (2015)	22	34	✓	-	✓	✓	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓	-
Lisee et al., (2019)	23	117	✓	✓	-	✓	✓	✓	✓	-	✓	-	-	-	-	-	✓	-	-	✓	-	✓	-	-	✓	-	-	-	-

Table 3.2 Summary of sample demographics and methods used to measure inter-limb strength asymmetry in the included articles (N = 53) ***continued***

			Sample Characteristics								**Strength Asymmetry Test**									**Sample Characteristics**									
											Isolated					**Functional**													
	Quality Score	**Total Sample Size (N)**	Male	Female	Injured/Post-Surgery	Uninjured	Athlete	Non-Athlete	Young (≤ 55 yrs.)	Old (> 55 yrs.)	Isokinetic Dynamometer	Stabilised Dynamometer	Hand-Held Dynamometer	Weight-Training Machine	Multi-Joint Strength Test	Nordic Hamstring	Jumping/Hopping	Push-Up	Seated Shot-Put	Torque	Force	Power	Impulse	Jump/Hop Height	Jump/Hop/Throw Distance	Vertical GRF	1-Repetition Maximum	Work Done	Rate of Force Development
Lloyd et al., (2020)	21	43	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	✓	-	-	-	✓	-	-	-	-
Lockie et al., (2012)	20	16	✓	-	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	✓	-	-	-	-	-	-	-	-
Lockie et al., (2014)	21	30	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	-	-	-
Lockie et al., (2013)	20	16	✓	-	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Lockie et al., (2016)	21	19	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-
Madruga-Parera et al., (2019)	22	41	?	?	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	-	-	-	-	-
Madruga-Parera et al., (2020)	20	42	✓	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	-	-	-
Maloney et al., (2017)	21	18	✓	-	-	✓	-	✓	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	-	-	-	-	-
Menzel et al., (2013)	20	46	✓	-	-	✓	✓	-	✓	-	✓	-	-	-	-	-	✓	-	-	✓	-	✓	✓	-	-	✓	-	✓	-
Miles et al., (2019)	22	66	✓	-	✓	✓	✓	-	✓	-	✓	-	-	-	-	-	✓	-	-	✓	-	-	✓	-	-	-	-	-	-
Opar et al., (2015)	22	210	✓	-	✓	✓	✓	-	✓	-	-	-	-	-	-	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-
Peebles et al., (2019)	23	30	✓	✓	✓	-	-	✓	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-
Redden et al., (2018)	24	13	✓	-	-	✓	✓	-	✓	-	-	-	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-
Reid et al., (2007)	23	42	✓	✓	✓	-	-	✓	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-
Riemann & Davies, (2019)	20	24	✓	✓	-	-	-	✓	✓	-	✓	-	-	-	-	-	-	-	✓	-	✓	-	-	-	✓	-	-	-	-
Suchomel et al., (2016)	22	13	✓	-	-	✓	-	✓	✓	-	-	-	-	-	-	-	✓	-	-	-	✓	✓	✓	-	-	-	-	-	✓

Table 3.2 Summary of sample demographics and methods used to measure inter-limb strength asymmetry in the included articles (N = 53) ***continued***

			Sample Characteristics								**Strength Asymmetry Test**									**Sample Characteristics**									
											Isolated					**Functional**													
	Quality Score	**Total Sample Size (N)**	Male	Female	Injured/Post-Surgery	Uninjured	Athlete	Non-Athlete	Young (≤ 55 yrs.)	Old (> 55 yrs.)	Isokinetic Dynamometer	Stabilised Dynamometer	Hand-Held Dynamometer	Weight-Training Machine	Multi-Joint Strength Test	Nordic Hamstring	Jumping/Hopping	Push-Up	Seated Shot-Put	Torque	Force	Power	Impulse	Jump/Hop Height	Jump/Hop/Throw Distance	Vertical GRF	1-Repetition Maximum	Work Done	Rate of Force Development
Vanderstukken et al., (2019)	21	50	✓	-	-	✓	✓	✓	✓	-	✓	-	-	-	-	-	-	-	-	✓	✓	-	-	-	-	-	-	-	-
Welling et al., (2019)	23	68	✓	-	✓	✓	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Xergia et al., (2013)	24	44	✓	-	✓	✓	-	✓	✓	-	✓	-	-	-	-	-	✓	-	-	✓	-	-	-	-	-	✓	-	-	-
Zwolski et al., (2015)	22	139	✓	✓	✓	-	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Zwolski et al., (2016)	22	45	-	✓	✓	✓	✓	-	✓	-	✓	-	-	-	-	-	✓	-	-	✓	-	-	-	-	-	✓	-	-	-
Total			44	25	23	42	33	22	52	1	25	1	2	3	3	2	28	1	2	24	13	7	6	14	18	4	1	2	1

GRF = Ground Reaction Force

3.4 Results

A total of 3,594 articles were retrieved from initial searches using PubMed, Scopus, SPORTDiscus with Full Text and Web of Science. A further 61 relevant articles were identified by reviewing the reference lists of the included articles. The title and abstracts of 1,264 articles met the screening criteria, and the remaining full-text articles that fulfilled the eligibility criteria were assessed for article quality (*n* = 288).

3.4.1 Article Quality Assessment

Most of the articles (*n* = 251, 87%) assessed for article quality scored ≥ 17, and the lowest scoring article received a total score of 9 out of 24. For 11 of the 12 criteria, over half of the 288 articles (57-97%) scored the maximum when each criterion was assessed individually (**Figure 3.2**). Typically, articles scored worse on CR3, which addressed sample size justification, with 147 (51%) articles scoring zero. The most common items that resulted in a score of 2 refer to the reporting of research objectives (CR1; 97%), utilisation of validated strength tests (CR9; 93%) and provision of an inter-limb asymmetry calculation (CR10; 91%). Of the 288 articles assessed, 149 (52%) received a total score of 20/24 and were considered for the full review. For the five selected criteria, the remaining 149 articles tended to score lower for reporting of the study protocol (CR6) and main findings (CR11). Fifty-three of the remaining articles scored 2 out of 2 on all five items and were included in the review.

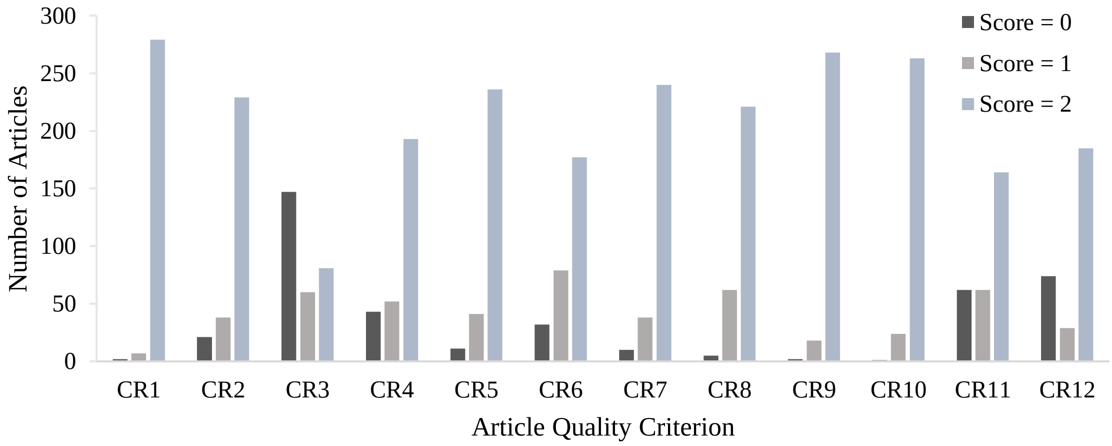

Figure 3.2 Distribution of quality scores for the articles assessed for eligibility (*n* = 288), where a score of 0 = No, 1 = Limited Detail and 2 = Yes (see **Table 3.1**)

3.4.2 Study Description

The included articles investigated a range of populations, including individuals who were injured or post-surgery, athletes, females and older individuals; however, some groups were less represented than others (**Table 3.2**). Sample groups were defined according to the definitions applied by the included articles. As such, participants referred to as 'athletes' or 'players' at any activity level were included in the athlete group and older adults included participants over 55 years as defined by the only article to investigate this population (Carabello et al., 2010). There was crossover for sample characteristics such that studies could be counted more than once, for example, female athletes following Anterior Cruciate Ligament Reconstruction (ACLR) would be counted in the female, athlete and post-surgery groups. Additionally, wheelchair users are not represented in this review despite stage two of the search strategy which was designed to retrieve studies investigating this sample demographic, as the related articles failed to fulfil the inclusion criteria. Various tests were implemented to measure inter-limb asymmetry in strength, power and functional performance outcomes including isokinetic dynamometry, stabilised dynamometry, hand-held dynamometry, weight-training machine tests, multijoint strength tests, the Nordic Hamstring test, push-up test and seated shot put test (**Table 3.2**). Some studies implemented multiple strength, power, or functional performance assessments, so were counted more than once across tests.

Twelve index types were identified from the literature (**Table 3.3**). The indexes were often referred to by different names and were applied for various limb comparisons. Five different methods of defining a limb comparison were made: 1) involved/uninvolved, 2) dominant/nondominant, 3) right/left, 4) stronger/weaker and 5) stance/skill. Limbs were sometimes referred to by different names but were grouped together, such as injured/uninjured instead of involved/uninvolved. For this review, the indexes were numbered from 1-12 to avoid confusion caused by inconsistent nomenclature but each article's specific terminology is also provided (**Table 3.3**).

Table 3.3 Asymmetry index types identified from the included articles (*N* = 53)

Index Calculation	Article	Index Name	Limb Comparison
1. $\frac{B}{A} \cdot 100$	Abourezk et al., (2017)	Limb Symmetry Index	Involved/Uninvolved
	Ageberg & Roos, (2016)	Limb Symmetry Index	Involved/Uninvolved
	Batty et al., (2019)	Limb Symmetry Index	Involved/Uninvolved
	Bookbinder et al., (2020)	Limb Symmetry Index	Involved/Uninvolved Dominant/Nondominant
	Fältström et al., (2017)	Limb Symmetry Index	Involved/Uninvolved Dominant/Nondominant
	Guney-Deniz et al., (2020)	Limb Symmetry Index, Quadriceps/ Hamstring Index	Involved/Uninvolved
	Harput et al., (2018)	Limb Symmetry Index	Involved/Uninvolved
	Hart et al., (2014)	Unilateral Strength Imbalance	Stance/Skill
	Holsgaard-Larsen et al., (2014)	Between-Limb Asymmetry Ratio	Involved/Uninvolved Dominant/Nondominant
	Hubbard et al., (2007)	Symmetry Index	Involved/Uninvolved
	Hughes et al., (2019)	Quadriceps/ Hamstring Index	Involved/Uninvolved
	Kaminska et al., (2015)	Limb Symmetry Index	Involved/Uninvolved Right/Left
	Lisee et al., (2019)	Limb Symmetry Index	Stronger/Weaker
	Lloyd et al., (2020)	Symmetry	Stronger/Weaker
	Peebles et al., (2019)	Limb Symmetry Index	Involved/Uninvolved
	Reid et al., (2007)	Limb Symmetry Index	Involved/Uninvolved
	Welling et al., (2019)	Limb Symmetry Index	Involved/Uninvolved Stronger/Weaker
	Xergia et al., (2013)	Limb Symmetry Index	Involved/Uninvolved Dominant/Nondominant
	Zwolski et al., (2015)	Quadriceps-Limb Symmetry Index	Involved/Uninvolved
	Zwolski et al., (2016)	Limb Symmetry Index	Involved/Uninvolved Dominant/Nondominant
2. $\frac{A}{B} \cdot 100$	Chmielewski et al., (2014)	Limb Symmetry Index	Dominant/Nondominant
	Clark & Mullally, (2019)	Limb Symmetry Index	Right/Left

Table 3.3 Asymmetry index types identified from the included articles (N = 53) *continued*

Index Calculation	Article	Index Name	Limb Comparison
3. $\left[1-\left(\frac{B}{A}\right)\right]\cdot 100$	Hadzic et al., (2014)	Strength asymmetry	Dominant/Nondominant
4. $100-\left[\left(\frac{B}{A}\right)\cdot 100\right]$	Almeida et al., (2019)	Limb Symmetry Index	Involved/Uninvolved
5. $\frac{100}{A}\cdot B\cdot -1+100$	Bishop et al., (2019c)	Asymmetry	Stronger/Weaker
	Bishop et al., (2019d)	Asymmetry	Stronger/Weaker
	Madruga-Parera et al., (2020)	Asymmetry	Stronger/Weaker
6. $\frac{A}{B}$	Ardern et al., (2015)	Bilateral Ratio	Stance/Skill
	Riemann & Davies, (2019)	Limb Symmetry Index	Dominant/Nondominant
7. $\frac{(A-B)}{A}\cdot 100$	Coratella et al., (2018)	Asymmetry	Stronger/Weaker
	de Lira et al., (2017)	Muscular Strength Asymmetry	Dominant/Nondominant
	Dos'Santos et al., (2018c)	Asymmetry Index	Right/Left Dominant/Nondominant
	Dos'Santos et al., (2017b)	Asymmetry Index	Right/Left Dominant/Nondominant
	Fort-Vanmeerhaeghe et al., (2016)	Asymmetry Index	Dominant/Nondominant Stronger/Weaker
	Fort-Vanmeerhaeghe et al., (2015)	Asymmetry Index	Stronger/Weaker
	Hiemstra et al., (2008)	Strength Deficit	Involved/Uninvolved
	Lockie et al., (2012)	Bilateral Difference	Stronger/Weaker
	Lockie et al., (2013)	Bilateral Difference	Stronger/Weaker
	Lockie et al., (2014)	Bilateral Asymmetry	Stronger/Weaker
	Lockie et al., (2016)	Asymmetry	Stronger/Weaker
	Madruga-Parera et al., (2019)	Asymmetry	Stronger/Weaker
	Vanderstukken et al., (2019)	Bilateral Strength Asymmetry	Stronger/Weaker
8. $\frac{(B-A)}{A}\cdot 100$	Carabello et al., (2010)	Asymmetry	Stronger/Weaker

Table 3.3 Asymmetry index types identified from the included articles (N = 53) *continued*

Index Calculation	Article	Index Name	Limb Comparison
9. $\frac{(A-B)}{Max(A,B)} \cdot 100$	Benjanuvatra et al., (2013)	Index of Asymmetry	Right/Left
	Dai et al., (2019)	Bilateral Asymmetry Index	Dominant/Nondominant
	Menzel et al., (2013)	Limb Symmetry Index	Right/Left
	Miles et al., (2019)	Asymmetry Index	Dominant/Nondominant Involved/Uninvolved
	Redden et al., (2018)	Percentage Difference	Right/Left
10. $\frac{(A-B)}{(A+B)} \cdot 100$	Suchomel et al., (2016)	Symmetry Index	Stronger/Weaker
	Costa Silva et al., (2015)	Bilateral Asymmetry Index	Dominant/Nondominant
11. $\frac{\left[45-\tan^{-1}\left(\frac{B}{A}\right)\right]}{90} \cdot 100$	Maloney et al., (2017)	Symmetry Angle	Right/Left
	Redden et al., (2018)	Symmetry Angle	Right/Left
12. $\ln\left(\frac{B}{A}\right) \cdot 100$	Bourne et al., (2015)	Between-Limb Imbalance	Right/Left Involved/Uninvolved
	Opar et al., (2015)	Between-Limb Imbalance	Right/Left Involved/Uninvolved

A = uninvolved/uninjured/non-operative/non-surgical, dominant/preferred, right, stronger/better performing, or stance/support limb value; B = involved/injured/operative/reconstructed/surgical, non-dominant/non-preferred, left, weaker/lesser performing, or skill/kicking limb value; * indicates the study used multiple indices, so appears more than once in this table

Index-1, often referred to as the Limb Symmetry Index, was the most used index across the included articles (n = 20) and provides an index of symmetry between limbs. Index-7 was the next most common (n = 13) but provides an index of asymmetry rather than symmetry. Of the 12 identified indexes, only four (Index-9, -10, -11 and -12) individually produced the same magnitude of asymmetry for scenarios 2 and 3 (Appendix 1, **Table A1.1**), demonstrating that they work independent of the limb that performs better (**Table 3.4**). However, not all scores were comparable to one another (Appendix 1, **Table A1.1)**. The stronger/weaker distinction was the only limb comparison that worked consistently across all 12 indexes, enabling each index to produce the same magnitude of asymmetry for scenarios 2 and 3, independent of direction.

Table 3.4 Analysis of asymmetry indexes for each identified limb comparison

Index Calculation	Limb Comparison				
	Involved/ Uninvolved	Dominant/ Nondominant	Right/ Left	Stronger/ Weaker	Stance/ Skill
$Index\ 1 = \frac{B}{A} \cdot 100$				✓	
$Index\ 2 = \frac{A}{B} \cdot 100$				✓	
$Index\ 3 = \left[1 - \left(\frac{B}{A}\right)\right] \cdot 100$				✓	
$Index\ 4 = 100 - \left[\left(\frac{B}{A}\right) \cdot 100\right]$				✓	
$Index\ 5 = \frac{100}{A} \cdot B \cdot -1 + 100$				✓	
$Index\ 6 = \frac{A}{B}$				✓	
$Index\ 7 = \frac{(A - B)}{A} \cdot 100$				✓	
$Index\ 8 = \frac{(B - A)}{A} \cdot 100$				✓	
$Index\ 9 = \frac{(A - B)}{Max(A, B)} \cdot 100$	✓	✓	✓	✓	✓
$Index\ 10 = \frac{(A - B)}{(A + B)} \cdot 100$	✓	✓	✓	✓	✓
$Index\ 11 = \frac{\left[45 - \tan^{-1}\left(\frac{B}{A}\right)\right]}{90} \cdot 100$	✓	✓	✓	✓	✓
$Index\ 12 = \ln\left(\frac{B}{A}\right) \cdot 100$	✓	✓	✓	✓	✓

A = uninvolved/dominant/right/stronger/stance/support limb value, and B = involved/nondominant, left, weaker, or skill/kicking limb value. Cells marked with a tick indicate that the calculation produces the same magnitude (ignoring direction) of asymmetry for scenario 2, when value A > B, as in scenario 3, when value A < B (i.e., the index works independent of which limb performs better), blank cells indicate that the calculation produces different magnitudes (ignoring direction) of asymmetry for scenarios 2 and 3

Thirty of the included articles referred to asymmetry scores in terms of a threshold (**Table 3.5**). Most commonly, asymmetry thresholds between 10-15% were described (*n* = 27); with twelve articles referring to a single threshold of 10%, eight articles referring to 15% and seven articles describing asymmetries at thresholds of 10% and 15%, two of which also investigated 20% asymmetry. The remaining articles (*n* = 3) used an alternative threshold of the mean + 0.2 standard deviations. Eighteen articles applied a threshold to original data, using a threshold defined in their methodology. Retrospective analysis of the evidence base revealed that 33% (*n* = 6) of the 18 articles provided Tier 1 or Tier 2 evidence (**Figure 3.3**).

Table 3.5 Strength asymmetry thresholds used by the included articles ($N = 53$) and the evidence level of each threshold applied in the methodology of the study

Article	Strength Asymmetry Threshold	Applied in methods (Y/N)	Evidence Tier
Bourne et al., (2015)	Investigated asymmetries above and below 10%, 15% and 20%	Y	1
Dos'Santos et al., (2017b)	Threshold: mean + (0.2 SD of the mean) Above the threshold = abnormal Below the threshold = normal	Y	1
Dos'Santos et al., (2018c)	Threshold: mean + (0.2 SD of the mean) Above the threshold = abnormal Below the threshold = normal	Y	1
Lockie et al., (2014)	Threshold: mean + (0.2 SD of the mean). Above the threshold = greater asymmetry group Below the threshold = lesser asymmetry group	Y	1
Opar et al., (2015)	Investigated asymmetries above and below 10%, 15% and 20%	Y	1
Holsgaard-Larsen et al., (2014)	Symmetry < 85% and > 115% = abnormal	Y	2
Fältström et al., (2017)	Symmetry < 90% and > 110% = abnormal	Y	3
Guney-Deniz et al., (2020)	Symmetry ≥ 90% = normal	Y	3
Menzel et al., (2013)	Asymmetry > 15% = abnormal	Y	3
Abourezk et al., (2017)	Symmetry ≥ 90% = normal Symmetry < 85% = abnormal	Y	4
Almeida et al., (2019)	Symmetry > 10% = abnormal	Y	4
Ardern et al., (2015)	Presence of deficits on at least 2 of the following: - Bilateral concentric hamstring peak torque ratio of 0.86 - Bilateral eccentric hamstring peak torque ratio of 0.86 - Concentric hamstring-quadriceps ratio of 0.47 - Mixed ratio of 0.80	Y	4
Batty et al., (2019)	Symmetry ≥ 90% = normal	Y	4
Clark & Mullally, (2019)	Asymmetry > 10% = abnormal	Y	4
de Lira et al., (2017)	Asymmetry > 15% = abnormal	Y	4
Hadzic et al., (2014)	Asymmetry > 15% = abnormal	Y	4
Welling et al., (2019)	Symmetry > 90% normal	Y	4
Zwolski et al., (2015)	Symmetry ≥90% = High quadriceps strength group Symmetry < 90% = Low quadriceps strength group	Y	4
Chmielewski et al., (2014)	Symmetry ≥ 85-90% = normal	N	n/a
Costa Silva et al., (2015)	Asymmetry < 15% = normal	N	n/a
Dai et al., (2019)	Asymmetry < 10% = normal	N	n/a
Fort-Vanmeerhaeghe et al., (2015)	Asymmetry > 10-15% = abnormal	N	n/a
Fort-Vanmeerhaeghe et al., (2016)	Asymmetry ≤ 10-15% = normal	N	n/a
Harput et al., (2018)	Symmetry ≥ 90% = normal	N	n/a
Lisee et al., (2019)	Symmetry ≥ 90% = normal	N	n/a
Lockie et al., (2012)	Asymmetry ≥ 15% = abnormal	N	n/a

Table 3.5 Strength asymmetry thresholds used by the included articles (*N* = 53) and the evidence level of each threshold applied in the methodology of the study (*continued)*

Article	Strength Asymmetry Threshold	Applied in methods (Y/N)	Evidence Tier
Lockie et al., (2016)	Asymmetry > 15% = abnormal	N	n/a
Miles et al., (2019)	Asymmetry < 10-15% = normal	N	n/a
Xergia et al., (2013)	Symmetry ≥ 90% = normal	N	n/a
Zwolski et al., (2016)	Symmetry > 90% = normal	N	n/a
Ageberg & Roos, (2016)	-	n/a	n/a
Benjanuvatra et al., (2013)	-	n/a	n/a
Bishop et al., (2019c)	-	n/a	n/a
Bishop et al., (2019d)	-	n/a	n/a
Bookbinder et al., (2020)	-	n/a	n/a
Carabello et al., (2010))	-	n/a	n/a
Coratella et al., (2018)	-	n/a	n/a
Hart et al., (2014)	-	n/a	n/a
Hiemstra et al., (2008)	-	n/a	n/a
Hubbard et al., (2007)	-	n/a	n/a
Hughes et al., (2019)	-	n/a	n/a
Kaminska et al., (2015)	-	n/a	n/a
Lloyd et al., (2020)	-	n/a	n/a
Lockie et al., (2013)	-	n/a	n/a
Madruga-Parera et al., (2019)	-	n/a	n/a
Madruga-Parera et al., (2020)	-	n/a	n/a
Maloney et al., (2017)	-	n/a	n/a
Peebles et al., (2019)	-	n/a	n/a
Redden et al., (2018)	-	n/a	n/a
Reid et al., (2007)	-	n/a	n/a
Riemann & Davies, (2019)	-	n/a	n/a
Suchomel et al., (2016)	-	n/a	n/a
Vanderstukken et al., (2019)	-	n/a	n/a

Y = Yes, N = No, n/a = not applicable, 1 = article provides the origin of the evidence for the threshold, 2 = article directly cites the origin of the evidence, 3 = article indirectly cites the origin of the evidence, 4 = article fails to provide or cite the origin of the evidence

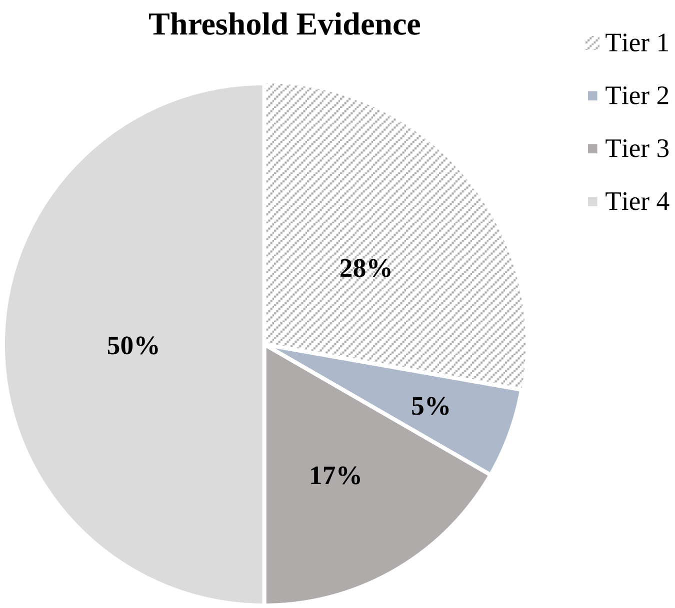

Figure 3.3 Evidence provided by the included articles for the asymmetry thresholds they employed, where Tier 1 indicates the article provides the origin of the evidence for the threshold, Tier 2 indicates the article directly cites the origin of evidence, Tier 3 indicates the article indirectly cites the origin of the evidence and Tier 4 indicates the article fails to provide or cite the origin of the evidence

3.5 Discussion

The aims of this systematic review were to 1) assess the appropriateness of quantitative methods for the calculation and interpretation of strength asymmetry, 2) assess the evidence base for asymmetry thresholds and 3) review normative levels of inter-limb strength asymmetry and its effects. This review summarises common practices for the study of inter-limb asymmetry in maximum and functional strength and provides an overview of normative values and effects as reported in the literature. This research highlights the importance of understanding the limitations of an approach when calculating asymmetry and interpreting scores across studies and methodologies.

3.5.1 Asymmetry Indexes

Various calculations have been documented in the literature to quantify inter-limb differences, many of which are referred to by multiple names and are used for different limb comparisons. Amongst the 53 articles included in this review, 12 distinct types of calculation were identified for five different limb comparisons (**Table 3.3**). Index-1, more commonly known as the Limb Symmetry Index, was the most used index (n = 20) and was applied across all five of the identified limb comparisons. Despite its widespread use, this index was identified by several other names, demonstrating inconsistency within the literature. This was also apparent for other commonly used indexes (Index-7 and -9). This potentially creates confusion when attempting to interpret the published literature, especially when indexes referred to by the same name produce inherently different scores. For example, in addition to Index-1, Index-9 (Menzel et al., 2013) and Index-4 (Almeida et al., 2019) were also referred to as the Limb Symmetry Index, despite fundamental differences in their arithmetic derivation. Furthermore, in some cases the naming of the index was inappropriate for the score produced, such as Index-10 which was referred to as the Symmetry Index (Suchomel et al., 2016), despite the calculation producing a score indicative of asymmetry rather than symmetry. Moreover, the Symmetry Index has been more generally described as the absolute difference between two sides divided by a reference value (Zifchock et al., 2008), where this value may be a single value or statistic of both sides. Thus, the Symmetry Index acts as an umbrella-term for a variety of calculations which produce a range of outcome scores. Such an inconsistent approach to index nomenclature is likely to create confusion when calculating and interpreting scores from any asymmetry index and requires the user to be vigilant to arithmetic variability.

Index-1 expresses the 'weaker' limb as a percentage of the reference limb, with the latter expected to be the stronger or better performing of the two limbs. Several other indexes also require the selection of a reference limb, providing either the contralateral limb or the difference between two limb values as a measure of the reference limb. Despite widespread use of this type of index, selecting one limb as a reference for strength or performance may be problematic, particularly when the selection is arbitrary. When investigating injured groups or patients after undergoing surgery, selection of the reference limb is more obvious, as the injured or operated side is likely to be weaker (Ageberg & Roos, 2016). Resultantly, the contralateral side often serves as the reference value. However, distinguishing between limbs becomes more challenging in uninjured samples as there is no clear choice between sides when using the right/left limb comparison and although the dominant limb is often stronger (Chmielewski et al., 2014; Dos'Santos et al., 2017b, 2018c; Hadzic et al., 2014; Miles et al., 2019), this is not always the case (Fältström et al., 2017; Fort-Vanmeerhaeghe et al., 2015, 2016). The stance/skill limb comparison can also be problematic if the stronger limb is not appropriately identified. In a study of sub-elite Australian Rules footballers, accurate kickers demonstrated better absolute strength on the support limb (Hart et al., 2014), which suggests it should serve as the reference value for asymmetry calculation. However, inaccurate kickers demonstrated better strength on the kicking limb, indicating that limb selection requires a more individual approach.

Irregular values may be produced if the reference limb fails to perform better than the contralateral side as demonstrated by index analyses using hypothetical scores. Index-1 failed to produce the same magnitude of asymmetry (ignoring direction) for scenario 3, when the contralateral limb was stronger, as in scenario 2, when the reference limb was stronger (**Table 3.4**). Index-2, -3, -4, -5, -6, -7 and -8 are similarly limited due to the need to select a reference limb. Therefore, indexes which require the selection of a reference limb may be inappropriate for describing inter-limb asymmetry and, at the very least, should be applied and interpreted with caution. It is also important to consider similarities and differences in the numerical derivation of each index which may be reflected in the score produced (Appendix 1, **Table A1.1**). Firstly, Index-1 and -2 both compute symmetry as a linear ratio between two limbs, where one limb is expressed as a percentage of the other. Index-3, -4 and -5 compute the score in a similar way but convert a score of symmetry to a score of asymmetry by subtracting the score from 1 before multiplying it by 100% (Index-3), by subtracting the percentage score from 100 (Index-4), or by multiplying the score by -1 and then adding 100 (Index-5). More simply, Index-6 used by Ardern et al., (2015) and Riemann and Davies, (2019) provides the reference limb as a ratio of the contralateral limb, whereas Index-7 and -8 divide the absolute difference between two limb values by a reference limb. Thus, researchers and practitioners are encouraged to ensure appropriate understanding of an asymmetry calculation before implementation and interpretation of scores.

Although eight of the identified indexes were unable to consistently produce the same magnitude of asymmetry across limb comparisons irrespective of which limb was stronger; they were able to produce the same magnitude of asymmetry when using the stronger/weaker limb comparison (**Table 3.4**; Appendix 1, **Table A1.1**). This indicates the stronger/weaker limb comparison can be used when selecting a reference limb without the associated limitations, as the asymmetry score is consistently normalised to the larger value produced by the two limbs. However, issues may arise for studies which assess reliability if the stronger limb fails to remain stronger in repeated measures, resulting in a lack of clarity in the results. This is also an important consideration for longitudinal studies and when comparing asymmetry between tests. An additional limitation of the stronger/weaker limb comparison is that it fails to identify the direction of asymmetry, such that the context of asymmetry may be lost. Nevertheless, these limitations may be overcome by utilising a logical 'IF' function to identify the direction of asymmetry without compromising the magnitude of the score (Bishop et al., 2019d, 2019c). Using this method, the asymmetry score can be converted to a negative value when a specified limb produces the higher value. It may therefore be argued that any of the 12 indexes identified in this review may be selected when using the stronger/weaker limb comparison; however, this limits the versatility of asymmetry computation. It should also be noted that the use of a reference value is suggested to be problematic for resolution in instances where the difference between two limb values is large compared to the absolute values (Herzog et al., 1989).

Of the 12 identified calculations used to assess asymmetry, only four (Index-9, -10, -11 and -12) functioned independently of which limb performed better (**Table 3.4**; Appendix 1, **Table A1.1**). These indexes separately produce the same magnitude of asymmetry for scenario 2 and 3, which is important when the reference limb is not the stronger limb or when it is challenging to discern between sides. However, each of the four indexes produce different scores which poses the question; which one to choose? Recent evidence suggests that the index should reflect the nature of the task; therefore, Index-9 has been recommended when assessing asymmetry from unilateral tests, as it involves normalisation of the absolute difference to the stronger limb value (Bishop et al., 2018a). This index avoids arbitrary selection of a reference limb and can be used in conjunction with an 'IF' function to identify the direction of asymmetry. However, this approach requires normalisation to a reference value which can lead to artificial inflation of asymmetry scores (Herzog et al., 1989). Alternatively, when implementing bilateral tasks, it has been argued that asymmetry should be computed as the absolute difference relative to the summed limb values (Index-10), in order to account for the contribution from both limbs (Bishop et al., 2018a). Despite this, Index-10 has also been used for single leg isokinetic assessments (Costa Silva et al., 2015), yet its use for unilateral tasks would not be recommended as it requires the use of data from separate trials, which is subject to variability. Moreover, Index-10 is more likely to deflate asymmetry scores, as it divides the absolute difference by the sum of both limb values, inhibiting resolution when making comparisons between test types and other indexes (Appendix 1, **Table A1.1**). Thus, test-specific indexes may not be appropriate for the calculation of inter-limb asymmetry, especially when a combination of both unilateral and bilateral tasks is implemented, as the scores are not comparable.

Alternatively, Index-11 does not rely on the selection of a reference limb or value. Also known as the Symmetry Angle (Maloney et al., 2017; Redden et al., 2018), the index has been proposed as a robust alternative, which defines an angle formed when a right-side value is plotted against a left-side value (Zifchock et al., 2008). Symmetry is achieved when two identical values create a 45° angle in relation to the x-axis. Index-12 similarly avoids the limitations associated with normalisation to a reference limb or value. Referred to as the Bilateral Limb Imbalance in the included articles (Bourne et al., 2015; Opar et al., 2015), the index is based upon the method proposed by Impellizzeri et al., (2008) which involves log-transformation of the ratio between two limbs. The log-transformed ratio can then be converted to a percentage by multiplying by 100. However, it was concluded by the authors that the bilateral ratios, as used to produce the index, have poor relative reliability and are more suitable for detecting large changes (Impellizzeri et al., 2008). Therefore, imbalance ratios may be useful when assessing inter-limb differences in injured groups but not so much in healthy individuals. It should also be noted that unlike the other indexes identified by this review, Index-11 and -12 produce non-linear outputs, such that one-unit changes in asymmetry are magnitude-specific. As a result, identical magnitudes of changes to asymmetry scores are unlikely to be associated with identical changes of magnitude of the raw input values, which could be challenging to interpret. It may also be argued that both Index-11 and -12 are inappropriate for the calculation of asymmetry as they fail to recognise the nature of the task (Bishop et al., 2018a); however, as previously described, test-specific indexes have other limitations. A paucity in the literature using both indexes necessitates that further investigation be undertaken to determine their suitability as compared to other commonly used indexes, considering both their precision and resolution.

To summarise, Index-9, -10, -11 and -12 are recommended over the other indexes identified by this review. This is based on their ability to express the magnitude and direction of asymmetry, thereby overcoming the limitations associated with selecting a reference limb. However, they fundamentally differ in computation, which is reflected in the magnitude of asymmetry, and this limits their relatability. Each index is also associated with other limitations as described in this review, which poses challenges when attempting to select an optimal approach. Therefore, in lieu of the literature adopting a standard unified index, it is recommended that investigators publish the raw data associated with their research, such that equivalent asymmetry scores can be calculated by the reader for the purpose of comparison using their personally preferred index. Researchers and practitioners are also encouraged to fully understand and interrogate their index of choice to ensure appropriate interpretation and comparison of asymmetry scores.

3.5.2 Asymmetry Thresholds

Thirty of the 53 articles in this review referred to an asymmetry threshold to indicate the point at which inter-limb difference in strength might be considered abnormal (**Table 3.5**). Amongst these articles, a threshold of 10-15% was most common, with a total of 27 articles referring to a threshold between these magnitudes. In support of this threshold, asymmetries larger than 10-15% have been associated with increased injury risk (Brumitt et al., 2013; Croisier et al., 2008; Fousekis et al., 2011) and reduced performance (Bishop et al., 2019d, 2019b, 2021b). Such evidence may explain the widespread use of a 10-15% threshold; however, no present consensus exists regarding the magnitude of asymmetry and its effects amongst specific groups. Recent evidence even indicates that athletes with inter-limb jump height asymmetries as low as 5% are susceptible to deficits in jumping, sprinting and change of direction performance (Bishop et al., 2019a). Disparities in the literature may be partly explained by the use of various asymmetry indexes that have the potential to produce largely different outcomes, as discussed above. Findings also highlight the sensitivity of asymmetry to methodology and sample characteristics, such that no single asymmetry threshold can be identified across the task, variable, or population that is assessed (Read et al., 2021). In addition, recent reports indicate asymmetries rarely favour the same limb across tests (Bishop et al., 2019c, 2021a; Madruga-Parera et al., 2020). Thus, an individualised approach to asymmetry assessment, considering the task, variables and population characteristics, may be necessary to avoid inappropriate use of generalised thresholds to identify abnormal asymmetry. Furthermore, thresholds should be supported by credible evidence if they are to be able to appropriately distinguish normal from abnormal asymmetry.

To overcome the limitations of using an arbitrary threshold, some investigators have determined group differences in strength asymmetry using the mean + 0.2 standard deviations (Dos'Santos et al., 2017b, 2018c; Lockie et al., 2014). It has been suggested that for elite team sport athletes multiplying the between-subjects standard deviation by

0.2 produces the smallest worthwhile change (Hopkins, 2004). This is based on Cohen's *d* effect size, whereby 0.2 corresponds to a small, but not trivial effect (Sullivan & Feinn, 2012). Using this calculation, participants above and below the threshold were classified accordingly, based on small but 'meaningful' differences in asymmetry. This provides a method for interpreting inter-limb differences without reliance on pre-determined thresholds that may not be suitable for the sample under investigation. When defining groups using 0.2 standard deviations of the mean, as done by several articles in this review (Dos'Santos et al., 2017b, 2018c; Lockie et al., 2014), the threshold between groups lies on the 58th centile of the entire sample. Alternative calculations have also been proposed, such as the mean ± 1.0 standard deviations (Graham-Smith et al., 2016) which shifts the threshold to the 84th percentile. Therefore, research is warranted to determine an appropriate magnitude for the smallest worthwhile change to identify the presence of meaningful differences in asymmetry between groups. However, in the absence of objective evidence linking cause and effect, any threshold, including those based on Cohen's *d* effect size, becomes arbitrary, simply describing the proportion of the population expected to fall within a group, rather than describing risk. Thus, when using such methods, researchers are encouraged to explore the effects of asymmetry on injury and performance within specific groups.

Strength tests are likely to incur error due to noise introduced by factors such as nutrition, environmental conditions, testing equipment and athlete preparation, which should also be considered when assessing asymmetry. Careful measurement protocols should be implemented to limit the noise associated with any given test so that it does not exceed the magnitude of the smallest worthwhile change. Exell et al., (2012) proposed that for inter-limb asymmetry to be considered meaningful, it must be larger than the intra-limb variability, which can be calculated using the coefficient of variation (Bishop et al., 2019d, 2019c; Dos'Santos et al., 2017b, 2018c; Madruga-Parera et al., 2020; Vanderstukken et al., 2019). Thus, only participants who display inter-limb differences greater than the sample-specific threshold and their individual variability may be interpreted as having meaningful asymmetry within the context of the sample, metric and test. It should be noted that this approach does not lend itself to the idea of, or investigation of, 'generic' asymmetry, thereby inhibiting comparisons between individuals. Yet, such an individualised approach to assessment of asymmetry is likely necessary in the future.

Retrospective analysis of the references revealed six of the 18 articles that applied a threshold to original research provided appropriate evidence, where the origin of the threshold was evidenced within the included article (Tier 1) or within its direct citations (Tier 2; **Table 3.5**; **Figure 3.3**). A study by Barber et al., (1990) was the oldest article to provide the origin of the evidence for a given threshold and appeared once in direct citations and twice more in indirect citations. In this study, a series of functional tests were implemented and thresholds of 80%, 85% and 90% were applied to assess normative symmetry in healthy controls. Of the three criteria investigated, 85% symmetry was identified in over 90% of the healthy controls under investigation during 2 of 3 functional tests, thus asymmetry larger than 15% was considered abnormal. Large deficits were observed between healthy and ACL-deficient knees during the three one-legged tests, such that only 50-58% achieved 85% symmetry and were classed as ‘symmetrical’. Statistically significant relationships were also observed among abnormal scores (> 15%) on the one-legged hop tests and self-assessed limitations for pivoting, cutting and twisting, quadriceps weakness and patellofemoral compression pain. This indicates functional limitations in individuals assessed by functional hop tests with asymmetries larger than 15%. As such, the authors concluded that 85% symmetry was sufficient to identify abnormal symmetry based on normative data in knee-healthy controls and functional outcomes in patients and controls. More recent evidence supports the use of this threshold, reporting increased risk of injury with asymmetries greater than or equal to 15% (Bourne et al., 2015). However, contradictory findings using the same index (Index-12) demonstrated no increase in hamstring strain injury risk for asymmetries of 10%, 15% or 20% (Opar et al., 2015). Evidence demonstrating the individual nature of asymmetry further undermines the use of arbitrary thresholds to determine abnormal asymmetry (Bishop et al., 2019c, 2019b; Dos’Santos et al., 2017c; Read et al., 2021). Therefore, evidence for the justification of an asymmetry threshold of 15% remains unclear.

Retrospective analysis of the articles that applied a threshold in the methodology of their study, revealed 67% provided Tier 3 or 4 evidence, as they failed to provide or directly cite the origin of the evidence (**Table 3.5**; **Figure 3.3**). Although Tier 3 articles provided the origin of the evidence in the indirect citations, Tier 4 articles failed to signpost the reader to appropriate evidence at all. Instead, Tier 4 articles often provided supporting references that failed to apply the threshold to original research (e.g., in a review or clinical commentary), could not be accessed in English and full-text, or failed to clearly evidence the threshold applied in the included article. For example, one article (Welling et al., 2019) applied a threshold of 90% symmetry based upon a consensus agreement achieved through survey responses (Lynch et al., 2015) rather than original research, and was classified as Tier 4 evidence as a result. Lower tiered evidence provides limited traceability and transparency and as such, Tier 3 and 4 articles were deemed weak evidence on which to base a given threshold. These observations suggest that some research studies are underpinned by poor referencing, and in some cases, the threshold in use may lack a robust scientific foundation.

In summary, retrospective assessment of asymmetry thresholds from this review demonstrates the need for more appropriate referencing within the scientific literature, where direct citations signpost the reader to the origin of the evidence. Furthermore, it should be noted that the quality of each evidence source was not interrogated beyond the application of asymmetry thresholds. Therefore, the quality of the research underpinning each threshold would require further investigation before application of pre-determined thresholds. In addition to the limitations of comparing asymmetry scores from different indexes, the lack of appropriate referencing suggests that the use of specific, pre-determined asymmetry thresholds may be flawed. This is particularly important for the use of thresholds between 10-15%, as they are often applied within asymmetry literature, yet they may lack the solid evidence-base necessary to rationalise their application to identify abnormal asymmetry. The lack of consensus within the literature further suggests that pre-determined thresholds should be avoided. Instead, an individualised approach to the interpretation of asymmetry should be adopted, which may utilise sample-specific thresholds and individual variability to identify asymmetry that can be considered real.

3.5.3 Normative Asymmetry and Subsequent Effects: Athletes

Athletes were well researched within the included articles ($N = 33$), but the definition of ‘athlete’ varied largely between articles. Therefore, participants that were described as ‘athletes’ or ‘players’ were considered as athletes in this review, which resulted in the inclusion of individuals participating at various levels of activity and competition. As such, strength asymmetry in athletes as reported in the literature, is likely to reflect diversity in the athletic population. Bilateral force asymmetries generally less than 10% have been reported amongst individual and team-sport collegiate athletes during a series of tests, including a countermovement jump (CMJ) and push up test (Dai et al., 2019). However, normative jump height asymmetries of 10-15% have been reported in male and female basketball and volleyball players (Fort-Vanmeerhaeghe et al., 2016). Furthermore, asymmetries up to 13% and 15% in isometric strength and hopping tasks have been reported amongst National Collegiate Athletic Association athletes without performance deficits (Dos'Santos et al., 2017b, 2018c). Individual and group mean peak torque asymmetries in excess of 15% have also been reported amongst team sport athletes (de Lira et al., 2017; Lockie et al., 2013), which undermines the commonly used 10-15% threshold. When interpreting these findings, the effect of index selection should also be considered as Dai et al., (2019) utilised Index-9, whereas Index-7 was used for the other investigations (de Lira et al., 2017; Dos'Santos et al., 2017b, 2018c; Fort-Vanmeerhaeghe et al., 2016; Lockie et al., 2013). Although both indexes produce the same magnitude of asymmetry for scenario 1, Index-7 produces inappropriate scores if the reference limb fails to perform better which would have implications for study comparisons (Appendix 1, **Table A1.1**).

When interpreting normative asymmetry in athletes, it is also important to consider the influence of sport and activity level on performance and limb imbalances. Group differences have been observed in absolute values for isokinetic torque (de Lira et al., 2017), jumping and push-up force (Dai et al., 2019) between athletes from different sports; however, no sport effect for strength asymmetry was observed (Dai et al., 2019; de Lira et al., 2017). Others have similarly reported no significant difference between activity level for symmetry in isokinetic and isometric peak torque, average power and hop distance (Lisee et al., 2019). Therefore, asymmetries appear less performance-level- and sport-specific, and more individualistic. However, the general consensus is that healthy athletes from recreational to elite level present inter-limb differences in strength of some magnitude. Therefore, perfect symmetry between limbs may not be an appropriate goal, nor an appropriate threshold against which to judge asymmetry. Additional sample characteristics should also be considered, as asymmetries in jumping and isokinetic torque reportedly vary as a function of maturation status (Madruga-Parera et al., 2019) and team-sport playing position (Costa Silva et al., 2015). Thus, sample characteristics should be considered when prescribing training interventions based on asymmetry assessments.

The presence of asymmetry in athletes indicates that it may not always be dysfunctional; however, researchers have reported weaker performance in association with increasing asymmetry. Hart et al., (2014) assessed the effect of isometric strength and lean mass asymmetry on kicking accuracy in sub-elite Australian footballers. Inaccurate kickers had significant asymmetry in lean mass, which translated to significant imbalance due to strength deficits in the support leg. However, strength adaptations in favour of the support limb have been documented (Bishop et al., 2020a), which highlights variability in the direction of asymmetry between the skill and support limb. It is often recommended that athletes work to achieve greater symmetry to improve technical proficiency and performance outcomes. In support of this, weaker performance in linear and change of direction tasks has been associated with strength asymmetry, such that athletes with larger asymmetries in isokinetic peak torque and some jump tests were slower (Bishop et al., 2019d; Coratella et al., 2018; Lockie et al., 2016; Madruga-Parera et al., 2020). Weaker performance may arise with increasing inter-limb asymmetry due to altered biomechanics or insufficient strength for the task resulting in inefficient movement and compensation strategies. Larger asymmetries have also been associated with reduced performance outcomes on both the dominant and non-dominant limb (Madruga-Parera et al., 2020) which makes it hard to discern the mechanism for effects of asymmetry on performance. In addition, findings indicate improved function amongst injured athletes with reduced post-surgery inter-limb asymmetry in isometric peak torque (Zwolski et al., 2015). Similar findings have also been reported in non-athletes with a history of ACLR (Bookbinder et al., 2020; Harput et al., 2018); however, this association does not demonstrate whether reduced asymmetry is the cause or effect of functional improvements.

Based on the association between strength asymmetry and reduced performance, it is often assumed that action should be taken to minimise asymmetry wherever possible. However, this notion is undermined by reports of asymmetries up to 13% in isometric strength and up to 15% in functional performance amongst collegiate athletes without detriment to change of direction speed (Dos'Santos et al., 2017b, 2018c). Furthermore, the direction of dominance was not always consistent between isometric strength or hopping and speed tests. Additionally, findings from Lockie et al., (2012) demonstrate better multi-directional speed performance in athletes with larger concentric torque and work differences between limbs. It is important, however, to consider that the authors may have sampled a largely symmetrical group of athletes, which could result in generally better speed performance. Furthermore, reports indicate a task specific nature of asymmetry, such that correlations have been observed for some tasks but not others

(Bishop et al., 2019d). Therefore, although some studies may demonstrate a lack of association between asymmetry and performance, and even beneficial associations in some cases, detrimental relationships may exist when the same sample is assessed using different methods.

Investigation into the effects of strength asymmetry on injury risk in athletes has become a well-researched topic as it is advocated that better competitive performance comes from minimising the time an athlete spends away from training through injury. One study assessed eccentric hamstring strength in 194 rugby players using the Nordic hamstring exercise and reported that force asymmetries of ≥ 15% and ≥ 20% increased the risk of prospective hamstring strain injury by 2.4-fold and 3.4-fold, respectively (Bourne et al., 2015). Larger inter-limb asymmetries may increase injury risk by altering movement mechanics however, a similar study observed contradictory findings, reporting no statistically significant increase in relative risk of future hamstring strain injuries in professional Australian rules footballer's with Nordic strength imbalances of 10%, 15% or 20% (Opar et al., 2015). Thus, the mechanism for injury in relation to inter-limb asymmetry remains unclear, as increased injury risk may arise due to lower pre-injury strength in either limb rather than inter-limb asymmetry per se. Differences in activity level may partly explain disparate findings, as one study recruited athletes from elite, sub-elite, and U19 premier-grade teams (Bourne et al., 2015) whereas, the other recruited elite athletes only (Opar et al., 2015). Furthermore, the first study took measurements during pre-season only (Bourne et al., 2015), whereas Opar et al., (2015) assessed asymmetry at three time-points throughout the season. Hence, differences in findings between studies may be partly attributed to strength adaptations in response to training (Nimphius et al., 2012). Although training for single-limb dominant sports may be expected to increase asymmetry between limbs due to increased exposure to one-sided tasks, asymmetry has been found to reduce over the course of a season in a sample of male youth soccer players (Lloyd et al., 2020). The lack of clarity might, therefore, reflect differences in study design and participant characteristics.

3.5.4 Normative Asymmetry and Subsequent Effects: Females

Females were also well researched by the studies examined in this review (n = 25); however, some studies presented male and female data combined, which poses challenges when attempting to understand asymmetry in females independent of their male counterparts. Several studies also failed to provide the sex of their participants.

Furthermore, differences in sample characteristics and methodological practices between studies pose limitations when attempting to compare results to male-only studies. Only 10 of the 53 included articles report strength asymmetry in female-only groups, suggesting that research investigating females separately from males is warranted.

One study investigated male and female National Collegiate Athletic Association Division I athletes and non-athletes across various sports and assessed the effect of sex on limb symmetry (Lisee et al., 2019). As expected, males demonstrated greater peak torque and power and outperformed their female counterparts during the single and triple hop for distance. However, no sex differences were observed in limb symmetry scores, with scores close to 95% limb symmetry on all hop-for-distance tests for both groups (Lisee et al., 2019). Close to perfect symmetry has also been reported during the single-leg hop for distance in healthy female athletes performing in both high- (Zwolski et al., 2016) and low-level sport (Fältström et al., 2017). However, Fort-Vanmeerhaeghe et al., (2016) found larger inter-limb asymmetries in females than males during the CMJ. Similarly large magnitudes of jump height asymmetry have been reported in physically active (19.3%), competitive (22.2%) and elite female athletes (14.1%; Benjanuvatra et al., 2013; Bishop et al., 2019d; Fort-Vanmeerhaeghe et al., 2015) which may indicate the CMJ has greater sensitivity to detect asymmetry between limbs. In support of this, Clark & Mullally, (2019) reported large individual asymmetries in female netball players during a unilateral vertical jump, such that over half of the participants were identified as having clinically significant asymmetry between limbs (> 10%), which was expected to increase the risk of injury. Comparatively, less than 9% participants were classified as asymmetrical for the triple hop and single leg hop for distance. Therefore, disparities in the literature regarding sex-differences are likely to reflect the task-specific nature of asymmetry. Anthropometric differences between sexes may also influence asymmetry, as non-normalised scores from a unilateral seated shot-put test were found to reflect differences in body size (Chmielewski et al., 2014).

When females were included in investigations, their data were rarely separated from the male data which makes it difficult to understand asymmetry in the female population. Nevertheless, findings from combined-sex data suggests the presence of inter-limb strength deficits in both males and females who are who are injured (Hubbard et al., 2007) or following surgery (Batty et al., 2019; Bookbinder et al., 2020; Guney-Deniz et al., 2020; Hiemstra et al., 2008), and these deficits are larger than for healthy controls (Bookbinder et al., 2020; Guney-Deniz et al., 2020; Hubbard et al., 2007). However, asymmetries following ACLR may be reduced over time through rehabilitation and functional knee bracing (Peebles et al., 2019). Furthermore, reduction in inter-limb asymmetry may be necessary to enhance performance during walking and jogging (Abourezk et al., 2017), and to improve knee function (Zwolski et al., 2015) and confidence post-surgery (Ageberg & Roos, 2016).

3.5.5 Normative Asymmetry and Subsequent Effects: Injury/Post-Injury

Twenty-three of the included articles recruited individuals who were injured or post-surgery. The literature generally indicates that injured individuals and patients' post-surgery demonstrate larger between-limb strength deficits than uninjured controls. One study reported greater isokinetic knee extension torque deficits at speeds of $120°\cdot s^{-1}$, $180°\cdot s^{-1}$ and $300°\cdot s^{-1}$, as well as greater hop asymmetry for individuals following ACLR compared to controls (Xergia et al., 2013). When averaged across speeds and hop tests, ACLR patients failed to reach the recommended asymmetry of less than 10-15% asymmetry (Index-1) in isokinetic strength (76.9%) and hop distance (82.4%), compared to controls (98.2% and 100.8%, respectively). Similarly, ACLR patients in a study by Holsgaard-Larsen et al., (2014) averaged 77.4% symmetry (Index-1) in involved versus uninvolved isometric hamstring peak torque. Yet, patients reached the recommended guidelines during the single-leg hop for distance, achieving 92.9% which highlights the task-specific nature of asymmetry. Therefore, a battery of tests may be necessary to overcome the limitations associated with task sensitivity and detect functionally relevant strength asymmetries.

Despite reports of patients achieving the recommended asymmetry of less than 10-15%, statistical significance has been found between ACLR and control groups (Holsgaard-Larsen et al., 2014). This suggests that even when the 10-15% threshold is achieved post-surgery; individual's still experience strength deficits compared to their healthy counterparts. Furthermore, research investigating the magnitude of asymmetry immediately following exercise demonstrates that patients following ACLR experienced improved limb symmetry in the single-leg hop for distance, such that scores improved from 4% less than controls pre-exercise, to 1.5% less than controls post-exercise (Bookbinder et al., 2020). This indicates differences in fatiguability between post-surgery and healthy groups, which may be the result of altered muscle architecture after ACLR (Noehren et al., 2016). However, the raw data should also be examined when interpreting asymmetry scores, as the goal should not be to improve symmetry by reducing performance on the stronger limb, which could be detrimental to performance. Significant group differences have also been reported between controls and participants with chronic ankle instability for asymmetries in isometric hip abduction force, ankle eversion average power and plantarflexion average power (Hubbard et al., 2007). However, no group differences were observed for any other ankle or hip strength and power outcomes, which indicates that asymmetry should also be interpreted in relation to the outcome variable that is assessed, as indicated previously (Bishop et al., 2019c, 2019b; Dos'Santos et al., 2017c; Read et al., 2021). Nevertheless, absolute values should be examined in addition to symmetry scores, as they may reflect effects on asymmetry that would be otherwise overlooked (Reid et al., 2007)

In addition to group differences between injured and control groups, differences have also been identified between injury types. For example, in one study non-athletes following combined anterior and posterior cruciate ligament injury demonstrated lower knee extension torque and work symmetry between limbs than those with an isolated injury to the anterior cruciate ligament (Kaminska et al., 2015). Group differences have also been identified in response to treatment type and rehabilitation. Improved limb symmetry in hamstrings and quadriceps peak torque was observed in soccer players from 4 to 10 months following ACLR and completion of a strength training protocol (Welling et al., 2019). At 10 months post-surgery, 65.8% of patients achieved limb symmetry larger than 90% for quadriceps strength and 76.3% for hamstring strength. Improvements in knee function were also observed at each time point post-surgery, demonstrating rehabilitation of limb symmetry to pre-injury levels when strength training is implemented. However, at 7- and 10-months following ACLR, the authors observed significantly improved quadriceps strength symmetry in soccer players treated with a hamstring tendon graft, compared to those treated with a bone-patellar tendon graft (Welling et al., 2019). In another study, patients treated with a bone-patellar tendon autograft similarly demonstrated improved symmetry in quadriceps peak torque at 5 to 8 months post-surgery compared to patients treated with a quadriceps tendon autograft (Hughes et al., 2019). This resulted in more patients with a bone-patellar bone autograft meeting criteria for return to running and return to play. These findings confirm the potential effect of surgical intervention type on rehabilitation of strength asymmetry following surgery, as previously reported (Machado et al., 2018; Welling et al., 2018).

3.5.6 Normative Asymmetry and Subsequent Effects: Older Adults

Individuals over the age of 45 years were rarely investigated in the included articles (*n* = 1) which indicates a paucity of research on older individuals within the asymmetry literature. The article in question reported similar relative asymmetry in 1-repetion maximum for healthy middle-aged adults (40-55 yrs.), healthy older adults (70-85 yrs.) and older mobility-limited adults (70-85 yrs.); however, the older mobility-limited group had significantly larger asymmetries in power (Carabello et al., 2010). They also consistently displayed asymmetries larger than the frequently cited 15% threshold and presented larger group standard deviations when compared to the healthy groups who demonstrated asymmetry magnitudes similar to those of young non-athletes for similar tasks and metrics (Lisee et al., 2019). However, Carabello et al., (2010) quantified asymmetry using Index-8, which is prone to inflation of scores when the reference limb fails to produce the larger value (Appendix 1, **Table A1.1**). Nonetheless, findings suggest strength asymmetry increases with age, which may be explained by a decline in muscle mass and quality (Goodpaster et al., 2006). Although the data indicates that older adults with mobility limitations have larger asymmetries in strength, it is unclear whether mobility limitations are the product of asymmetry or whether asymmetry is simply exacerbated by existing mobility limitations. Therefore, further research is warranted in adults over the age of 45 years to better understand the effect of age on asymmetry.

3.5.7 Limitations

There are some limitations to this review. Firstly, the search strategy limited results to articles available in English which may introduce language bias. Similarly, articles were required to be readily available in full-text which may have led to the exclusion of otherwise relevant studies. The use of filters as part of the search process means some citations may have been excluded if the indexing process of the relevant database was incomplete. Although article quality assessment is important to reduce the risk of bias and ensure the quality of a review (Shamseer et al., 2015), there is a lack of consensus in the literature regarding selection of an appropriate tool that can be used across study designs as required by this review. Therefore, a modified article quality tool originally designed for the assessment of non-randomised studies (Peters et al., 2010) was used in this review. Thus, it should be noted that quality scores generated in this review and by other studies in the literature may not be comparable to scores generated by alternative methods. The use of the article quality tool in this review demonstrates poor quality amongst many articles within the Sport and Exercise Science field. In particular, articles within this area failed to utilise *a priori* sample size calculations to justify their samples which may introduce sample size bias. It is recommended that future studies justify their sample size prior to investigation. In scenarios where this is not feasible, the authors should be able to appropriately justify the sample size and identify it as a limitation where relevant. Additionally, evaluation of the five article quality items selected based on their importance to this review, demonstrated weak quality of reporting for study protocol and main findings in this area of research. Improper protocol reporting poses challenges when attempting to replicate research, which draws into question whether results are valid and reliable when they cannot be fairly interrogated by the scientific community. To be included in this review, articles were required to report their results as the mean, standard deviation and *P* value where appropriate, to ensure fair comparison between studies. Therefore, it is possible that some otherwise high-quality articles that utilised alternative statistical reporting methods were excluded.

3.6 Conclusion

In conclusion, this review demonstrates disparate practice with regards to the calculation and interpretation of inter-limb strength asymmetry, with numerous strength tests and asymmetry indexes in use and inconsistent interpretation of scores using threshold boundaries. Index-9, -10, -11 and -12 were the only indexes able to overcome the limitations associated with selection of a reference limb or value. However, additional issues should be considered when calculating inter-limb asymmetry by any of these methods as none of the indexes produced the same magnitude of asymmetry as another. Further investigation is also necessary to determine whether they are capable of achieving sufficient precision and resolution when computing asymmetry across tasks and metrics. The use of pre-determined, arbitrary thresholds to determine what is “normal” should be avoided, especially as commonly used thresholds, such as between 10-15% are not robustly supported by the literature. Such methodological limitations are likely to contribute to the lack of consensus regarding the magnitude of inter-limb differences in strength and the subsequent implications for injury and performance. Therefore, practitioners should interpret asymmetries in strength with caution due to inherent limitations associated with methodological practices, and the interchangeable use of various indexes in the literature. Going forward, an individualised approach to asymmetry assessment may be necessary, which considers the use of sample-specific thresholds and individual variability. It is also vital that various populations are investigated to address future research questions so variability and similarities between groups can be explored further.

Chapter 4: General Methodology

4.1 Chapter Overview

This chapter describes the methodological procedures implemented for the experimental chapters of this thesis including participant recruitment, ethical considerations, as well as data collection, processing and analyses. Chapter 5 utilises a sample of data from Chapter 6 and Chapter 7 which pertain to original data from two main data collection periods. Procedures that relate to any one study are described in the methods section of the relevant chapter. All experimental studies were conducted at the Biomechanics laboratory on Clifton Campus at Nottingham Trent University.

4.2 Participants and Recruitment

For all experimental chapters of this PhD, young and healthy, team-sport athletes were recruited (see Section 4.3). The University's sports department, NTU Sport, were initially contacted following which, identified coaches were invited to advertise the study to their university athletes. Potential participants were provided with a 'participant information' document describing the study aims and design, eligibility criteria, procedures and techniques involved and requirements of participation (Appendix 2, A2.1-A2.2). Potential risks and hazards associated with the research, as well as benefits, including a feedback report of their data (accessible to themselves and their coach) were also outlined. The feedback report included performance and asymmetry data which the recipient was advised to interpret with their coaching team according to the available body of literature. Voluntary participation was emphasised in the document and data protection procedures according to university policy were explained. Individuals who subsequently volunteered to participate were provided with a statement of informed consent (Appendix 2, A2.3-A2.4) and a health screen questionnaire (Appendix 2, A2.5) a minimum of 24 hours prior to study participation. Upon visiting the lab, the study protocol was explained again in full, and participants were given the opportunity to ask questions or raise concerns regarding study procedures.

4.3 Inclusion/Exclusion Criteria

For both experimental studies (Chapter 6 and Chapter 7), male and female team-sport athletes were recruited. Participants were required to be aged between 18-35 years old and affiliated to the British University & Colleges Sport (BUCS) League during the data collection season. Participation in a primary sport involving principal use of the lower limbs for at least one year was also required (i.e., if participating in multiple sports, the primary sport was identified as the sport requiring the greatest time commitment per week). Basic training and match load data were recorded at all assessment timepoints, using a Training Report Form (Appendix 3, A3.1) completed by the participants University coach.

Participants were required to be healthy, free from any lower-limb musculoskeletal injury in the 6 months preceding and during the data collection period, and without any known illness or pathology that would affect performance in the research. Any criteria that would exclude the participant from the study was also identified by the health screen questionnaire. For longitudinal data collection (Chapter 7), participants were also asked to highlight any injuries that occurred during the study period and complete an Injury Report Form (Appendix 3, A3.2). Athletes that were no longer eligible to participate in the study were withdrawn.

4.4 Ethical Approval

Ethical approval was sought for Chapter 6 and Chapter 7 from the Nottingham Trent University Human Invasive Ethics Committee. A single ethics application was initially submitted to address both cross-sectional (Chapter 6) and longitudinal (Chapter 7) data requirements. The ethics application was later extended following amendments to cover additional procedures adopted for the cross-sectional study (Chapter 6).

4.5 Measurement of Anthropometrics

Participant height was measured when standing barefoot on a stadiometer, with feet flat and heels against the backplate. The buttocks, back and head were required to be in contact with the vertical board of the stadiometer for measurement. Participants were instructed to take a deep breath in whilst maintaining an upright posture and the stadiometer headboard was brought down to reach the most superior aspect of the head. Height was measured to the nearest 0.1 cm, ensuring the measurement was not obstructed by the participants' hair.

Participant body mass was measured when standing barefoot, with the feet shoulder width apart on digital scales. Participants were instructed to wear minimal clothing (i.e., sports bra/top and tight-fitting shorts) and to stand upright, with the head facing forward. Body mass was recorded to the nearest 0.01 kg, whilst the participant remained still.

4.6 Measurement of Functional Strength

4.6.1 Force Platform Measurements (Jumping)

Jump testing was conducted in Chapter 6 and Chapter 7 to measure dynamic functional strength. Apart from obvious differences in study design (longitudinal vs cross-sectional), the procedures for data collection were identical. A motion capture system (Nexus v2.14, Vicon Motion Systems Ltd, Oxford, UK) was used to collect kinetic data from an embedded multiaxial, dual-force plate system (AMTI, Watertown, MA, USA) sampling at 1000 Hz (model no: BMS400600, dimensions: 40cm × 60cm, capacity: 9000 N). Participants were instructed to keep their hands positioned on the hips throughout the trial. For bilateral task variations, participants stood with one foot in the centre of each force platform. For unilateral task variations, participants were instructed to stand in the centre of the force platform which corresponded to the side being tested, with the free knee flexed to approximately 90°. Two jump tests were performed: 1) vertical countermovement jump for height (CMJ) and 2) horizontal jump for distance (HJ). Three maximal effort trials of each test were conducted separated by 60 s of rest between trials. Unsuccessful trials were repeated following a 60 s rest period. Instructions for each task were the same for all participants and consistent feedback was provided to ensure proper technique.

For the CMJ, instructions were to squat down to a self-selected depth and rapidly explode upwards to achieve maximal height. Swinging of the free limb during unilateral trials was not permitted to minimise the effect of the contralateral limb on the jump outcome in a similar mechanism to arm swing (Lees et al., 2004). Participants were instructed to avoid excessive hip or knee flexion during the airborne phase of the jump and to land with minimal flexion of the knees and hips. To encourage maximal effort, participants were instructed to adopt their preferred landing strategy on either one or two feet, regardless of the nature of the task. A trial was considered successful if there was no excessive flexion of the hips or knees during the flight phase, hands remained on the hips throughout and an extended, upright landing was adopted.

For the HJ, participants were instructed to align their toes directly behind the start line marked on the force plate and jump as far as possible to achieve maximal distance. As detailed above for the CMJ, swinging of the free limb during unilateral trials was not permitted and participants were instructed to adopt their preferred landing strategy on either one or two limbs. A trial was considered successful if the first landing foot did not move after contact with the ground and hands remained on the hips throughout. To minimise learning effects, participants were asked to complete additional trials if their jump distance improved by more than 10 cm between trials. Jump distance was measured using a tape measure, as the perpendicular distance from the start line at take-off to the heel of the first landing foot.

4.6.2 Force Platform Data Processing (Jumping)

Methods of data collection remained identical across Chapter 6 and Chapter 7; however, Chapter 7 only required uniaxial kinetics (vertical force) and temporal data to calculate jump height using the flight-time method (see JH_1 described below). Chapter 6 utilised the multiaxial kinetic data to enable calculation of peak force and jump height as per the take-off velocity method (see JH_2 described below). Accordingly, there are some differences in processing and reporting of metrics (described below). Vertical and horizontal ground reaction forces were extracted unfiltered and subsequently copied into a custom-made Microsoft Excel spreadsheet for analysis following recommendations (Chavda et al., 2020; McMahon et al., 2018). Unfiltered, non-smoothed data was used according to recommendations for analysis of maximal effort jump performance (Street et al., 2001). An initial quiet standing phase with the participant stood upright was required before the onset of each trial to enable accurate measurement of bodyweight (average vertical force during a stable 1 s period, **Figure 4.1**). The onset of the movement was defined using a vertical force threshold equal to five standard deviations of the magnitude of bodyweight which has been shown to reduce the probability of incorrect identification (Dos'Santos et al., 2017a; Owen et al., 2014). As movement has already begun at this point, velocity is not equal to zero and so, a threshold 30 ms prior to the onset of the movement was identified for subsequent calculations (**Figure 4.1**).

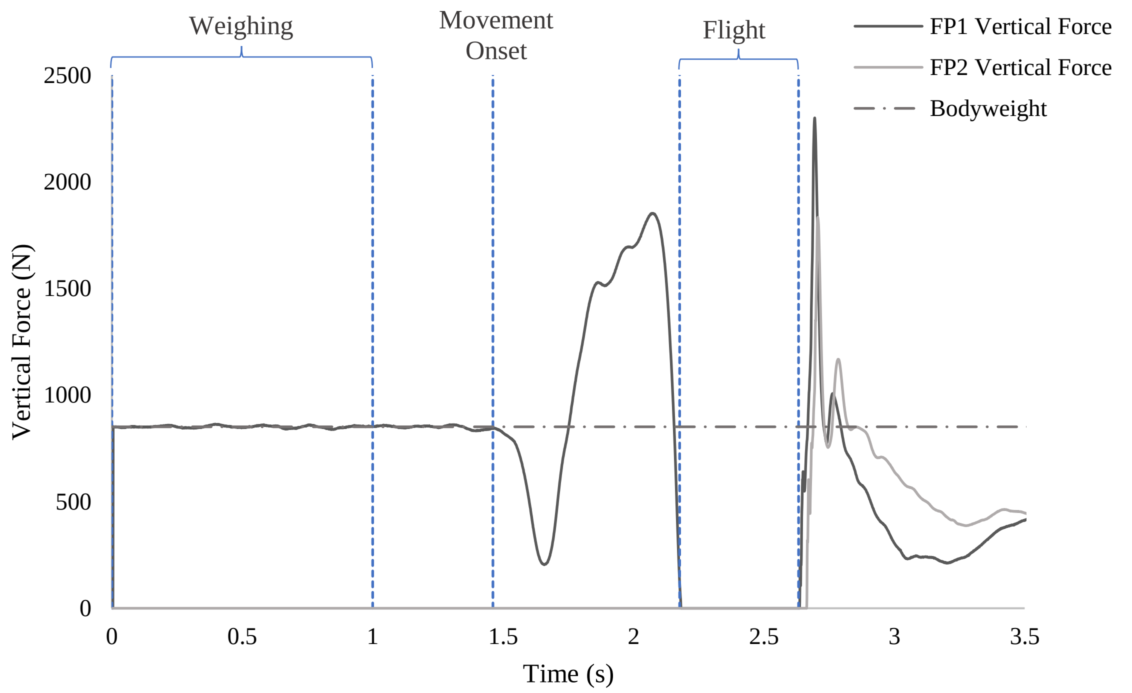

Figure 4.1 Example force-time profile for a unilateral countermovement jump between the start of weighing to just after landing, with weighing, movement onset and flight identified.

The magnitude of bodyweight was subtracted from the vertical force to give net vertical force for subsequent calculations. Centre of mass (CoM) acceleration was calculated as net vertical force divided by body mass, and impulse and velocity were calculated by integration using the trapezoid rule of the force-time and acceleration-time profiles, respectively. Negative impulse was identified from movement onset up until peak negative (downward) CoM velocity was reached (end of unweighting), which occurs as vertical force returns to the magnitude of bodyweight and net force is zero (**Figure 4.2**). Positive impulse was identified thereafter up to the point of take-off (**Figure 4.2**) defined as the instant when vertical force crossed a threshold equal to five times the standard deviation of the vertical force during the first 300 ms of flight. This method has been recommended as it accounts for variability in the data due to signal noise and reduces the risk of misidentifying the take-off threshold (Chavda et al., 2018).

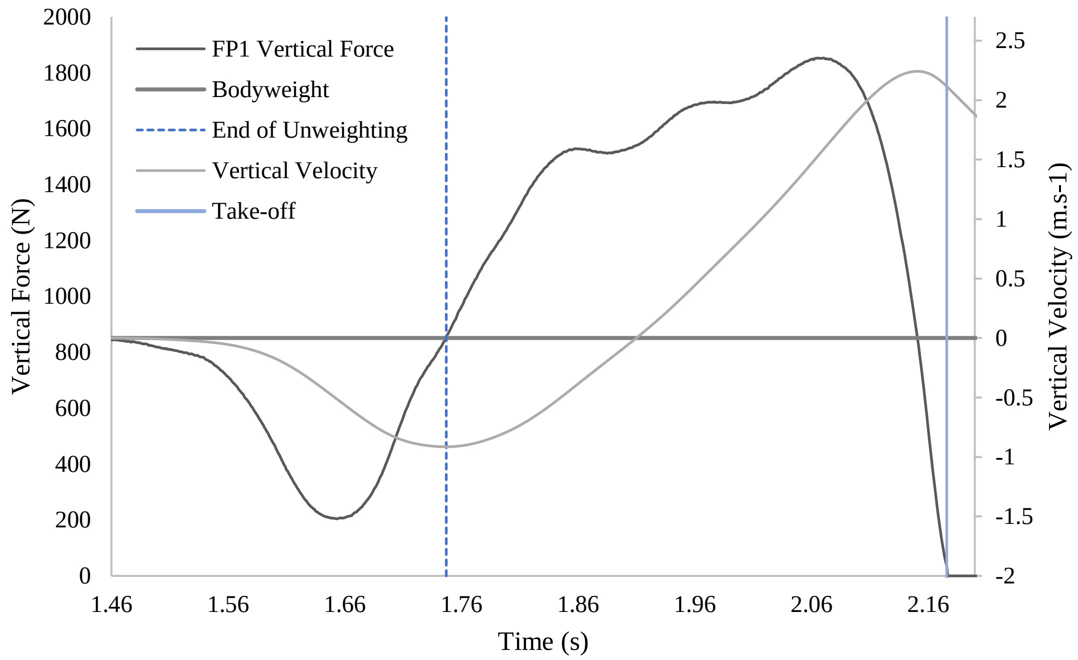

Figure 4.2 Example force-time (solid black line) and velocity-time (solid grey line) profile for a unilateral countermovement jump between the onset of movement and just after take-off

For the CMJ, jump height was calculated using either the flight-time (Equation 1; Chapter 7) or take-off velocity (Equation 2; Chapter 6) methods.

$$JH_1 = 0.5 \cdot a(t/2)^2 \tag{1}$$

Where, JH_1 = jump height (m) using the flight-time method (1), a = acceleration due to gravity (m.s^{-2}), t = total flight time (s).

$$JH_2 = TOV^2/2 \cdot a \tag{2}$$

Where, JH_2 = jump height (m) using the take-off velocity method (2), TOV = vertical velocity of the centre of mass at take-off (m.s^{-1}), a = acceleration due to gravity (m.s^{-2}).

The flight-time method (JH_1) calculates vertical displacement from time in the air, which is the premise of jump mats commonly used in applied practice. However, the method assumes the position of the CoM at take-off and at landing are the same which can lead to artificial inflation of jump height (Hatze, 1998; Moir, 2008). Instead, the take-off velocity method (JH_2) involves integration the force-time profile to calculate vertical velocity at take-off using the impulse-momentum relationship. Unlike the former, it is not affected by differences in CoM position at take-off and landing, but the method requires some technical knowledge, more expensive equipment and can be more time-consuming.

Landing was identified using a vertical force threshold of 10 N and peak propulsive force from the CMJ was identified as the maximum net vertical force value before take-off. For the HJ, resultant force was calculated from net vertical force and horizontal force using Pythagoras' Theorem, and peak propulsive force was identified as the maximum resultant force before take-off.

4.6.3 Force Platform Measurements (Isometric Midthigh Pull)

The IMTP was conducted in Chapter 7 to measure isometric functional strength. The IMTP was conducted using a portable rig (MTP Portable, serial no: 27469/1, Indigo Fitness, Nuneaton, UK) with a uniaxial dual-force plate system (PASPORT force plate, PASCO Scientific, California, USA), sampling at 1000 Hz (model no: PS-2141, dimensions: 35 cm × 35 cm, capacity: 6600 N). For bilateral task variations, participants were instructed to stand with the feet in the centre of each force platform (**Figure 4.3a**). For unilateral task variations, participants were instructed to stand in the centre of the force platform which corresponded to the side being tested, with the free knee flexed to approximately 90° (**Figure 4.3b**). Participants first performed two warm-up trials (3 s submaximal pull at 50% and 75% of their perceived maximum effort) followed by three maximal effort trials lasting 5 s, each separated by 60 s of rest. Unsuccessful trials were repeated following a 60 s rest period. Instructions for each task were the same for all participants and consistent feedback was provided to ensure proper technique. Strong encouragement was provided throughout performance to ensure maximum effort (Belkhiria et al., 2018).

Test procedures were conducted in line with previous recommendations (Comfort et al., 2019). Participants were instructed to assume a body position that replicated the second pull phase of the power clean (DeWeese et al., 2013) specifically, a neutral forward-facing head position and upright torso, slight flexion at the knees, shoulders retracted and depressed, thighs in contact with the bar, and feet approximately hip width apart and centred roughly under the bar (**Figure 4.3)**. The height of the bar was determined individually for each athlete during familiarisation to ensure optimal joint angles at the knee (125-145°) and hip (140-150°) were obtained (where full joint extension corresponds to 180°; Beckham et al., 2012, 2012; Dos'Santos et al., 2017d). Joint angles were measured using a standard goniometer with its axis aligned with the lateral femoral epicondyle and the goniometer arms in line with the longitudinal axis of the thigh and shank segments. Participants were instructed to apply minimal pre-tension to the bar before the onset of the movement, and to remove any joint ‘slack’ that could result in undesirable joint angle changes during performance (Beckham et al., 2018; Maffiuletti, 2016). To limit the effect of grip strength and variability, all participants held onto the bar using weight-lifting hooks and were instructed to position the hands next to the thighs (Rhodes et al., 2022). Standardised instructions to “drive your feet into the ground as hard and fast as possible” were given to ensure maximum force during maximal effort trials (Halperin et al., 2016). Trials were considered successful if there was no observable countermovement or excessive pre-tenson, and a stable 1 s weighing period was present before the onset of the pull (DeWeese et al., 2013; Maffiuletti, 2016).

a) **b)**

Figure 4.3 Isometric midthigh pull stance for a) bilateral and b) unilateral task variations

4.6.4 Force Platform Data Processing (Isometric Midthigh Pull)

Vertical ground reaction forces were extracted unfiltered and subsequently copied into a custom-made spreadsheet. There is no consensus for an optimal approach on filtering and smoothing IMTP data but, filtered data has been shown to underestimate kinetics due to misidentification of movement onset for isometric testing (Dos’Santos et al., 2018a). An initial quiet standing phase with the participant stood in the correct posture (described above) was required before the onset of each trial to enable accurate measurement of bodyweight (average vertical force during a stable 1 s period just prior to movement onset, **Figure 4.4**). Pull onset was defined using a vertical force threshold equal to five standard deviations of the magnitude of bodyweight (**Figure 4.4**) which has been shown to reduce the probability of incorrect identification (Dos'Santos et al., 2017a). The same threshold was also used to identify excessive countermovement missed by manual inspection. The magnitude of bodyweight was subtracted from the vertical force to give net vertical force for calculation of peak force (N) and relative peak force ($N \cdot kg^{-1}$).

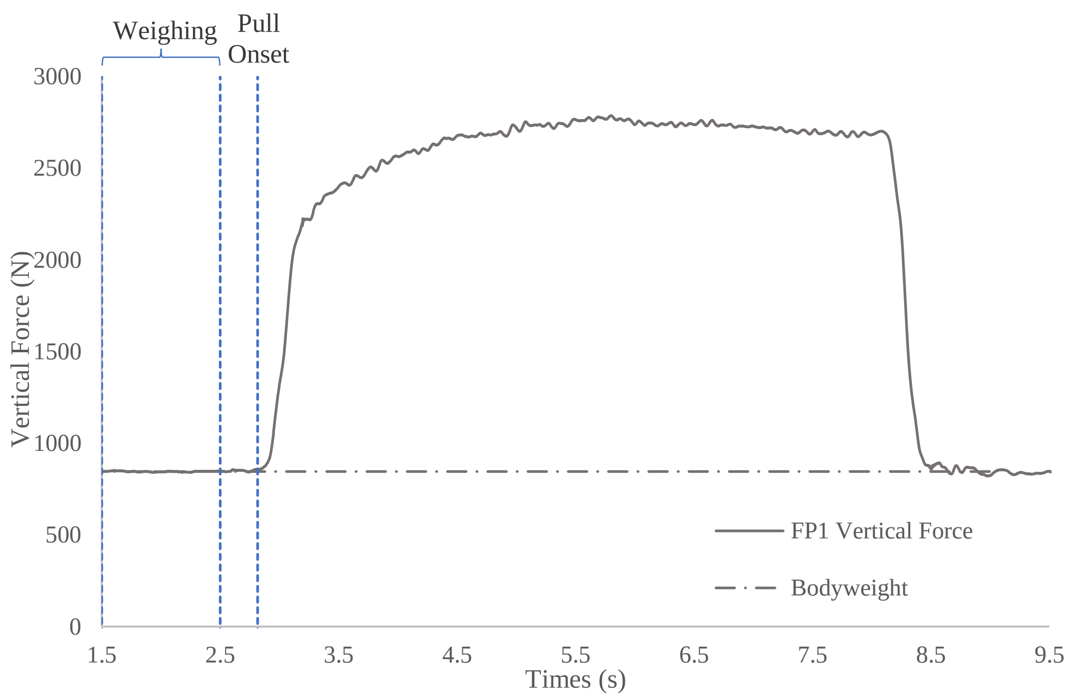

Figure 4.4 Example force-time (solid black line) profile for a unilateral isometric midthigh pull between the start of weighing to just after bar release, with weighing and pull onset identified.

4.7 Measurement of Maximal Strength

4.7.1 Dynamometer Measurements

Maximum isometric strength testing was conducted on the isokinetic dynamometer in Chapter 6 and a subset of the data (one participant) was used to fulfil the experimental aim of Chapter 5. Isometric knee flexor and knee extensor torque measurements were collected using a Humac NORM isokinetic dynamometer (CSMi, Stoughton, MA, USA), sampling at 100 Hz. Participants were seated on the dynamometer according to manufacturer guidelines for knee flexion/extension testing and strapped securely at the torso, hips, thigh and shank to minimise any movement which would have undesirable effects on torque-angle measurements. Given that angular differences between crank and joint angles during contraction can be large (Arampatzis et al., 2004, 2005), the functional joint centre (lateral femoral epicondyle) was aligned with the dynamometer crank axis under submaximal load and the joint positioned near the optimal angle (near full extension for the knee flexors and in the mid-range for the knee extensors). The dominant limb, identified subjectively by the participant as the limb that they would kick a football with (McCurdy & Langford, 2005), was tested first during knee flexion and then knee extension to minimise learning and fatiguing effects before testing of the non-dominant limb in the same order.

There is no consensus for the number or location of joint angle measurements when determining isometric joint torque-angle characteristics. For this research, a selective protocol was implemented to cater to demands of both clinical and applied practices whereby time for extensive data collection and processing can be limited. Participants performed one trial at five tested joint angles: (20°, 40°, 60°, 80° and 100° depending on their available joint range of motion, where 0° = anatomical zero or full extension). In instances where the participant could not flex the limb to 100°, a joint angle of 90° was used instead. Each contraction lasted 5 s and was followed by a minimum of 60 s of rest. Two minutes of rest was provided during changes between limbs (dominant to non-dominant) or muscle groups (knee flexion to knee extension). Instructions were to "push/pull as fast and hard as possible" during the contraction and encouragement and visual feedback were provided throughout each trial to encourage maximal effort (Campenella et al., 2000; Rendos et al., 2019). For consistency across tests, torque and angle data were extracted unfiltered and unsmoothed for processing.

4.7.2 Gravity Correction

The measured crank torques were corrected using angle-specific passive torque functions determined from three controlled passive motion trials, during which the relaxed limb was moved at a slow velocity ($10°\cdot s^{-1}$) through the full range of motion. Passive torque data were fitted using a fourth order polynomial which closely fitted the experimental data. Angle-specific passive torques were then added or subtracted from measured peak torque at each tested crank angle depending on whether the muscle group was working with or against gravity. This process corrects measured torque by accounting for the weight of the limb and the resistance exerted by passive structures which contribute to stiffness variability throughout the joint range of motion (McHugh & Hogan, 2004).

4.7.3 Joint Kinematics

A standard goniometer was used to measure the participant's knee joint angle during contraction due to the potential for joint-crank axes misalignment during contraction

(Arampatzis et al., 2004, 2005). This was particularly expected for the knee flexors due to the chair-participant interface which allows more scope for upward translation. The goniometer axis was aligned with the lateral femoral epicondyle and the goniometer arms were positioned along the longitudinal axis of the thigh and shank segments. Goniometer joint angles were recorded as the angular distance from horizontal and corrected against crank angles using linear regression for derivation of the torque-angle relationship.

4.7.4 Torque-Angle Representation

Modelling techniques allow for the controlled investigation of a single variable's effect on the system and can eliminate unavoidable measurement errors. In the context of isokinetic dynamometry, errors in torque-angle measurements may arise due to lack of familiarisation, fatigue and misalignment of the crank/joint axes (Appen & Duncan, 1986; Arampatzis et al., 2004, 2005; Dirnberger et al., 2012; Nugent et al., 2015; Winter et al., 1981). Modelling the torque-angle relationship may therefore improve estimates of isometric strength and can be used to better understand movement and performance in simulation models and reality. The torque-angle relationship has been modelled previously using a quadratic function (King et al., 2006, 2012; Lewis et al., 2012) or a bell-shaped curve (Forrester et al., 2011). A quadratic function was selected for this work (Chapter 5 and Chapter 6 Chapter 6) as it has been shown to better represent isometric joint torques measured at the knee (Equation 3; Lewis, 2011).

$$T_\theta = \left(1 - k_2\left(\theta - \theta_{opt}\right)^2\right).T_0 \tag{3}$$

where T_θ represents joint torque at angle θ calculated by the quadratic function, k_2 represents the width or curvature of the quadratic, θ_{opt} is the optimal angle for torque production and T_0 is the peak isometric torque.

Parameter values were determined through optimisation to fit measured torque and minimise a cost function (Corana et al., 1987). Simulated annealing is a stochastic search method for solving unconstrained and bound-constrained problems. The algorithm uses probabilistic numerical methods to determine the acceptance or rejection of new points in an attempt to lower the system energy (or cost function). By accepting some potentially 'bad' moves which raise the objective function, simulated annealing avoids being trapped in local minima in early iterations and expands the search for a global optimum. This method has previously been used to determine strength parameters for isometric profiles of the knee flexors and extensors (Forrester et al., 2011; King et al., 2012)

The performance of the search algorithm can vary in relation to the nature of the problem, and it should be adequately tailored to the problem it is tasked to solve. A critical aspect in optimisation strategies is the cost function, which provides a measure of model performance (Yeadon & King, 2008). A root mean square (RMS) of the difference between measured (input) and predicted (output) values was selected for this research, with unweighted (Chapter 5) and weighted (Chapter 5 and Chapter 6) variations applied depending on the problem to be solved (Equation 4; adapted from King et al., 2012).

$$RMS = \sqrt{\frac{w_1 \sum_{i=1}^{n} x_i{}^2 + w_2 \sum_{j=1}^{m} y_j{}^2}{n w_1 \sum_{i=1}^{n} + m w_2 \sum_{j=1}^{m}}} \tag{4}$$

For data points where the measured torque > the function value (i); w_1 = weighting of points larger than the function value (i), n = the number of data points, x_i = difference between measured torque and the function value, and likewise for data points where the measured torque < the function value (j); w_2 = weighting of points less than the function value (j), $m =$ the number of data points, y_j = difference between measured torque and the function value.

Typically, the torques measured during isometric conditions are expected to be close to be maximal due to minimal neural inhibition compared to concentric or eccentric work (Babault et al., 2001). In such scenarios, an unweighted cost function, were $w_1 = 1$ and $w_2 = 1$, can be suitable (**Figure 4.5**). This approach was adopted for the simulated data derived from literature-sourced parameters (Chapter 5). Isometric torques may, however, be submaximal due to lack of familiarisation and fatigability, as well as reduced neural drive at longer muscle lengths (Kubo et al., 2004). In this case, a weighted cost function would be necessary to avoid a submaximal representation of torques, resulting from a predominantly one-sided error (**Figure 4.5**). This approach was adopted for the original data described in Chapter 5 and Chapter 6.

The weighting of the cost function was determined in a simulated dataset (*N* = 1000) modelled from literature-sourced parameters for torque-angle profiles of the knee flexors and knee extensors (King et al., 2012). Submaximal noise associated with the experimental data was first determined by prediction of measured torque using a central difference approach, where measured data were used to predict torque at alternate angles throughout the curve. One-sided error of approximately 10% were identified and served as the lower threshold for random noise incorporated into the simulated dataset. All parameters were constrained to physiologically realistic upper and lower bounds. Following investigation of various weighting combinations in the simulated dataset, weightings of 100 and 1 were assigned to w_1 and w_2, respectively, as fitted torques closely matched the underlying theoretical torque-angle profiles without noise (RMS difference < 1% of maximum). The likelihood of underestimating peak torque was also reduced from -7% using an unweighted function to -3% using the weighted approach.

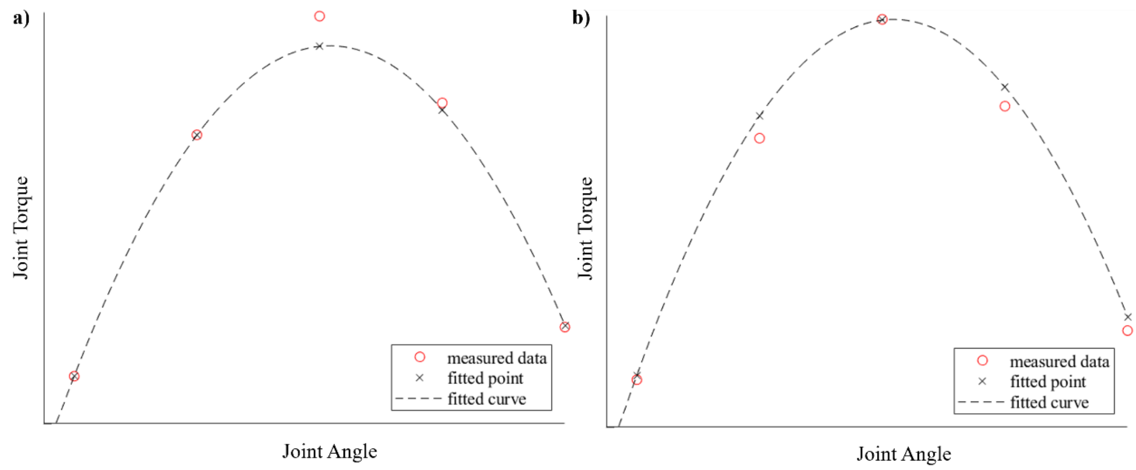

Figure 4.5 The effect of a) an unweighted and b) a weighted (w_1 = 100, w_2 = 1) cost function on the joint torque-angle representation

4.8 Statistical Analyses

4.8.1 Descriptive Statistics and Normality Assessment

The two trials with best performance for all functional strength tests were identified and exported to SPSS (version 29.0 for Windows, Armonk, NY: IBM Corp) for analyses conducted in Chapter 6 and Chapter 7. All original data were assessed for normality using the Shapiro-Wilk test and by visually inspecting boxplots. Skewness/kurtosis and extreme outliers were identified using z-score thresholds of ± 1.96 and ± 3.29, respectively. Some variables were identified as non-normally distributed ($p < 0.05$) and were subsequently log-transformed to ensure parametric test assumptions were not violated.

4.8.2 Reliability Assessment

Within-session reliability of the functional strength tests (Chapter 6 and Chapter 7) was computed for the two trials using the coefficient of variation (CV) and an average measures two-way mixed effects intraclass correlation (ICC) for absolute agreement with 95% confidence intervals (CI) was conducted. Calculation of the CV was performed on the raw data (before log-transformation), with values < 10% considered acceptable (Cohen, 1960; Lakens, 2013). Interpretation of the ICC was in accordance with Koo & Li, (2016) where: > 0.90 = excellent, 0.75-0.90 = good, 0.50-0.74 = moderate and < 0.50 = poor).

4.8.3 Asymmetry Calculation

Inter-limb asymmetries were quantified from unilateral tests conducted in Chapter 6 andChapter 7, to detect both asymmetry magnitude and direction between limbs (Parkinson et al., 2021). For functional tests, the mean of the two trials was used (Equation 5):

$$ASI = \frac{(A-B)}{Max(A,B)} \cdot 100 \tag{5}$$

where *ASI* = asymmetry index score (%), *A* = right or dominant limb value, *B* = left or non-dominant limb value. Kappa coefficients were calculated to determine the levels of agreement in the direction of asymmetry (i.e., how consistently the same limb was favoured) between limbs and/or tests. Kappa values were interpreted as ≤ 0 = poor, 0.01-0.20 = slight, 0.21-0.40 = fair, 0.41-0.60 = moderate, 0.61-0.80 = substantial and 0.81-0.99 = almost perfect (Cohen, 1960; Viera & Garrett, 2005)

4.8.4 Effect Size Calculation

Following any statistical analyses performed in Chapter 6 and Chapter 7, the magnitude of differences was calculated as per recommendations from Cumming, (2011) using Cohen's d for larger samples ($n \geq 20$) or a corrected effect size (Hedges, g) for smaller samples ($n < 20$), with 95% confidence intervals (Lakens, 2013). Cohen's d was calculated for either a paired (Equation 6) or independent (Equation 7) design according to the comparison being made, from which the corrected effect size could be calculated (Equation 8).

$$d_1 = \frac{M_{diff}}{s_{av}} \quad (6)$$

Where, d_1 is Cohen's uncorrected effect size for paired comparisons (1), M_{diff} is the mean of the differences and s_{av} is the average standard deviation.

$$d_2 = \frac{(M_2 - M_1)}{s_p} \quad (7)$$

Where, d_2 is Cohen's uncorrected effect size for independent comparisons (2), M_1 and M_2 are the two group means and s_p is the pooled standard deviation.

$$g = d\left[1 - \frac{3}{4(n_1 + n_2 - 2) - 1}\right] \quad (8)$$

Where, g is Hedges' corrected effect size, d is Cohen's uncorrected effect size (d_1 or d_2) and n_1 and n_2 are the sample sizes for each comparison. Effect sizes were interpreted according to Hopkins et al., (2009), where < 0.2 = trivial, 0.2-0.6 = small, 0.6-1.2 = moderate, 1.2-2.0 = large, 2.0-4.0 = very large and > 4.0 = near perfect. Confidence intervals were calculated on the uncorrected effect size using a t-distribution for comparisons in a smaller sample size (Cumming, 2011; Nakagawa & Cuthill, 2007).

4.9 Summary

This chapter described the methods undertaken to complete the research for this PhD. Details specific to any given study are reported in the relevant chapter with any additional procedures and analyses. The next chapter utilises experimental and computational methods to investigate various measurement protocols implemented for the assessment of isometric knee strength using the gold-standard method, isokinetic dynamometry.

Chapter 5: Joint Torque-Angle Characteristics: Assessing the Accuracy of Experimental Determination

5.1 Rationale

The systematic review detailed in Chapter 3 highlights the various methodological approaches for the assessment of strength and associated asymmetries, using both lab- and field-based methods. The results demonstrate widespread use of the gold-standard method, isokinetic dynamometry, adopted by 25 of the 53 articles identified by the search. Peak torque at the knee joint was assessed most often, with assessments of the knee flexors and knee extensors accounting for 80% of the articles utilising isokinetic dynamometry. Despite its establishment within research and practice, there is currently no standard practice for the measurement of torque-angle characteristics, such as isometric peak torque, which has led to protocol variability with respect to the number and location of tested joint angles in both experimental and modelling literature. To assess maximum isometric strength, measurements must be made at the optimal joint angle for torque production, yet individual variability in torque-angle characteristics (Brughelli et al., 2010; Herzog & ter Keurs, 1988b; Kellis & Blazevich, 2022; Kulig et al., 1984) limits the generalisability of any one protocol. Therefore, dynamometry measurements may not reflect the true capability of the musculature to produce torque about the joint, which undermines the accuracy of strength-related metrics and indices. Thus, the purpose of this chapter is to investigate the accuracy of isokinetic dynamometry protocols for the assessment of isometric strength characteristics at the knee. The chapter employs a data simulation approach to investigate the effect of measurement approach to 1) assess peak isometric torque from measurements at a single joint angle and 2) to predict torque-angle characteristics from torque measurements at multiple joint angles. A measurement approach with multiple joint angles is then adopted in an experimental dataset to assess the utility of selective protocols for prediction of torque-angle characteristics.

5.2 Introduction

Muscular strength can be attributed to the force producing capability of individual muscles to produce joint torque, which enable human movement via segmental rotations about the joint axis. The ability of the surrounding musculature to produce torque is governed by the muscle force-length relationship, which at the joint level (torque-angle relationship) commonly displays a bell-shaped curve (Edman & Reggiani, 1987). However, the shape of the joint torque-angle profile differs between individuals and muscle groups (Brughelli et al., 2010; Frasson et al., 2007; Herzog et al., 1990; Herzog & ter Keurs, 1988b; Kellis & Blazevich, 2022; Kulig et al., 1984; Savelberg & Meijer, 2003) due to variability in muscle structure and architecture (i.e., muscle thickness, pennation angle and fibre type) that influence torque-angle characteristics, specifically the optimal angle, peak isometric torque and width. For example, the optimal angle amongst cyclists was reported to be larger during knee flexion and smaller during knee extension (i.e., shorter muscle lengths) compared to that amongst Australian Rules football players which reflect differences in muscle architecture (Brughelli et al., 2010). Furthermore, knee flexion peak torque occurs when the joint is more extended (Brughelli et al., 2010; Kellis & Blazevich, 2022; Mohamed et al., 2002), whereas knee extension peak torque occurs near the middle of the joint range of motion (Brughelli et al., 2010; de Sousa et al., 2023; Marginson & Eston, 2001; Pincivero et al., 2004). Adaptations due to training have also been reported, indicating shifts of the torque-angle profile towards longer muscle lengths due to sarcomeregenesis (Douglas et al., 2017), which can prove useful for injury mitigation and performance enhancement (Brughelli & Cronin, 2007; Delextrat et al., 2020; Marušič et al., 2020; Ribeiro-Alvares et al., 2018). It is, therefore, important to take an individual approach to ensure accurate assessment of joint torque-angle characteristics in research and applied practice.

The isokinetic dynamometer is generally considered the gold standard for measuring torque-angle characteristics due to its high reliability when measuring isometric and isokinetic peak torque *in vivo* (de Araujo Ribeiro Alvares et al., 2015; Maffiuletti et al., 2007; Tsiros et al., 2011). The isokinetic dynamometer also provides a safe and controlled environment for maximal effort testing, particularly during isometric conditions where the muscle contracts at static crank angles, and muscle-tendon unit length is maintained. This reduces the risk of joint or muscle overloading and reduces the risk of injury. Although isokinetic dynamometry is predominately used for research investigating strength (Brown et al., 2014; Sørensen et al., 2021), it has also been utilised in sport and health settings to aid training, injury prevention and rehabilitation (Bagordo et al., 2020; Douglas et al., 2017; Herbawi et al., 2022). Despite this, there is no consensus on an optimal protocol which poses implications for the interpretation and comparison of results.

Numerous measurement approaches exist for the assessment of isometric torque-angle characteristics for joint actions throughout the human musculoskeletal system. Peak torque during isometric contractions of the knee musculature has previously been measured at a single joint angle, with 90° from anatomical zero commonly used within the literature (Bampouras et al., 2017; Blazevich et al., 2009a; Bojsen-Møller et al., 2005; Hori et al., 2020). Yet, single measurement angle approaches are likely to result in a systematic underestimation of strength if peak torque measurements are made at suboptimal joint angles and referred to as 'maximal'. Protocols utilising multiple measurement angles have also been implemented (Bakenecker et al., 2019; Baroni et al., 2013; Bogdanis et al., 2019; de Brito Fontana & Herzog, 2016; De Groote et al., 2010; Guenzkofer et al., 2011; Heinen et al., 2019; Hume et al., 2018; Lanza et al., 2017; McHugh & Tetro, 2003; Onambele-Pearson & Pearson, 2007; Pincivero et al., 2004), with as many as eleven measurement angles adopted to estimate torque-angle properties of the knee extensors (Chow et al., 1999b). Such approaches improve the likelihood of measuring peak torque close to the optimal angle and provide more information about the shape of the torque-angle profile; however, the effect of the number and location of measurement angles tested across the joint range of motion has not been investigated. Multiple torque measurements are also compounded by suboptimal variability (de Carvalho Froufe Andrade et al., 2013; Maffiuletti et al., 2007) and extensive experimental protocols require an abundance of time for data collection and analysis that is not available in many research and applied environments. A more refined and technical approach may, therefore, be required when assessing isometric torque-angle characteristics.

Curve fitting techniques have been used to predict joint torque-angle characteristics for use in torque-driven simulation models, where subject-specific parameters are optimised to fit torque-angle data collected on an isokinetic dynamometer (Conceição et al., 2012; Heinen et al., 2019; King et al., 2012; Lewis et al., 2012, 2018, 2021). A simple quadratic function has been used previously to display the torque-angle relationship in a monoarticular representation of the joint (King et al., 2012; Wilson et al., 2006).

Modelling techniques such as this, have useful applications in research and practice as they can be used to better understand human movement and optimise performance (Felton et al., 2020; Wilson et al., 2006; Yeadon & King, 2002; Yoshioka et al., 2010). It is important, therefore, that model parameters are accurately determined to ensure appropriate movement patterns are attained, yet there is no clear consensus on this methodology. As a result, various approaches with multiple measurement angles exist and their effect on the accuracy of curve-fitting techniques to predict individual joint torque-angle profiles is unknown.

Data simulation approaches are becoming more popular to investigate methodological hypotheses since they allow for the controlled investigation of the effect of a single variable on the effect of the system. For example, a recent study used a data simulation approach to replicate and systematically investigate relationships reported in previous studies between body mass, vertical jump performance and sprint performance (McErlain-Naylor & Beato, 2022). These processes also maximise the potential to generate new knowledge and hypotheses within biomechanics whilst retaining privacy and ethics (Warmenhoven et al., 2020); however, it is ultimately necessary to explore the application of such approaches in experimental data to assess their validity. The initial aims of this study were, therefore, to use a data simulation approach to; 1) investigate the effect of joint angle location in a single measurement angle approach to assess peak torque, and 2) investigate the effect of joint angle number and location in a multiple measurement angle, curve fitting approach to predict joint torque-angle characteristics. The final aim was to explore a curve-fitting approach to predict torque-angle characteristics of original data collected using a selective isokinetic dynamometry protocol.

5.3 Methods

5.3.1 Joint Torque-Angle Representation and Parameters

A three-parameter quadratic function (King et al., 2012; Wilson et al., 2006) was used to describe the relationship between torque production and joint angle in a monoarticular representation of the knee joint (see Section 4.7.4, Equation 3). Subject-specific parameters for peak isometric torque (T_0), optimal angle (θ_{opt}) and width (k_2) for the knee flexors and knee extensors (**Table 5.1**) were identified from literature sources which reported both joint actions under isometric conditions. Three eligible articles were retrieved but only two provided independent datasets. Both original investigations provided torque-angle parameters for a single subject; 1) an elite male cricket fast bowler (age: 18 years, mass: 85 kg, height: 1.935 m; Felton, 2015); and 2) a male volleyball athlete (age: 28 years, mass: 79.2 kg, height: 1.74 m; King et al., 2012).

Table 5.1 Knee joint torque-angle parameter values from identified articles

	Description	Knee Flexion			Knee Extension		
		Felton (2015)	King et al., (2012)	Bounds (LB; UB)	Felton (2015)	King et al., (2012)	Bounds (LB; UB)
T_0 (Nm)	Peak isometric torque	188.00	118.55	±20% of T_0	430.00	185.69	±20% of T_0
θ_{opt} (°)	Optimal angle for peak torque	146	179	131.78; 206.26	231	242	177.62; 315.13
k_2	Width of torque-angle profile	0.26	0.39	0.2; 2.0	0.80	1.64	0.2; 2.0

*Bounds taken from King et al., (2012), LB = lower bound, UB = upper bound

To aid interpretation of the width parameter, which is a scaling factor for the curvature of the joint torque-angle profile, the distance between the optimal angle and one of the roots of the quadratic was calculated in degrees and denoted as the 'half range' (**Figure 5.1**). All joint angles are reported in relation to agonist muscle length i.e., angles correspond to the posterior angle for knee flexion and the anterior angle for knee extension, where a joint angle of 180° represents anatomical zero.

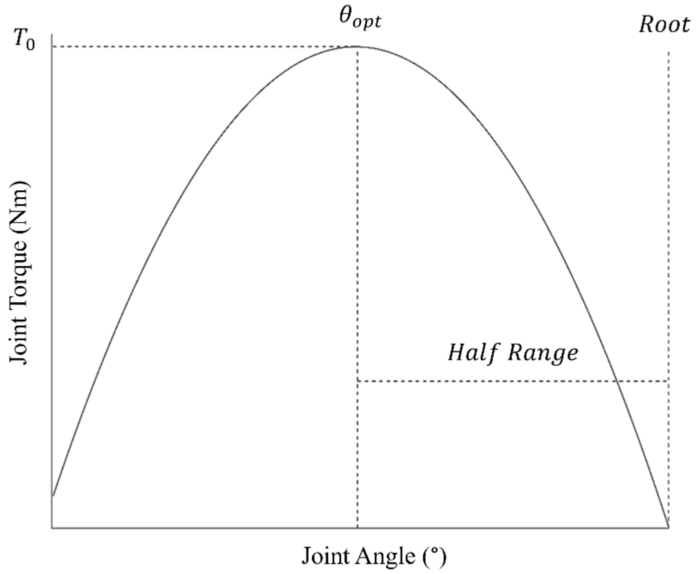

Figure 5.1 Example quadratic torque-angle profile, displaying model parameters; T_0 = peak isometric torque, θ_{opt} = optimal angle and Half Range computed as the distance (°) between θ_{opt} and one of the quadratic roots where joint torque is equal to zero

5.3.2 Aim 1: The effect of joint angle location in a single measurement angle, isokinetic dynamometry approach to assess peak torque

A simulated dataset was generated for this aim using the literature-sourced joint torque-angle parameters and quadratic function (Equation 3; **Table 5.1**). A series of individual joint torque-angle profiles were determined by perturbing the optimal angle (using intervals of 2°) and width (using intervals of 0.01) between the minimum and maximum parameter values identified (**Table 5.1**). This resulted in 294 and 935 individual joint torque-angle profiles for each assessment of the knee flexors and knee extensors, respectively. The simulated torque was expressed as a percentage of peak isometric torque (T_0) with 100% representing the peak isometric torque for each individual profile.

The effect of measuring peak torque at suboptimal joint angles was investigated for a series of joint angles commonly used for strength assessments of the knee flexors; 90°, 120° and 150°; and knee extensors; 230°, 240° and 270° (Horstman et al., 2009; Krishnan & Williams, 2014; McHugh & Tetro, 2003; Muanjai et al., 2020; Worrell et al., 2001). The absolute difference between the joint torque at each measurement angle and the peak isometric torque (100%) for each individual joint torque-angle profile was calculated and referred to as 'torque error'. For example, if peak isometric torque is 100 Nm (100%) and the measured torque is 97 Nm (97% of true maximum), a torque error of 3% exists.

5.3.3 Aim 2: The effect of joint angle number and location in a multiple measurement angle, curve fitting approach to predict torque-angle characteristics

A new simulated dataset was generated for the second aim to represent joint torque data collected on an isokinetic dynamometer at multiple measurement angles throughout the knee joint range of motion. Initially, an original joint torque-angle profile was created for each joint action (flexion/extension) using the quadratic function (Equation 3) and the parameters reported by King et al., (2012; **Table 5.1**).

Measurement angles were located at 10° intervals throughout the joint range of motion (determined independently for each joint action). This resulted in ten measurement angles for knee flexion (joint range: 90-180°; **Figure 5.2a**) and nine measurement angles for knee extension (joint range: 200-285°; **Figure 5.2b**). A series of raw torque-angle datasets ($N = 100$) were then created by subtracting random noise between 0 and 10 Nm (generated using MATLAB, R2020a, Natick, Massachusetts, The MathWorks Inc.) from the original joint torque data at each measurement angle throughout the joint range. The noise threshold (-10 Nm) was identified in experimental data using a central difference method approach to predict torque at alternating joint angles (described below in Section 5.3.4) and represents suboptimal variability which can exist in repeated joint torque measures (de Carvalho Froufe Andrade et al., 2013; Maffiuletti et al., 2007).

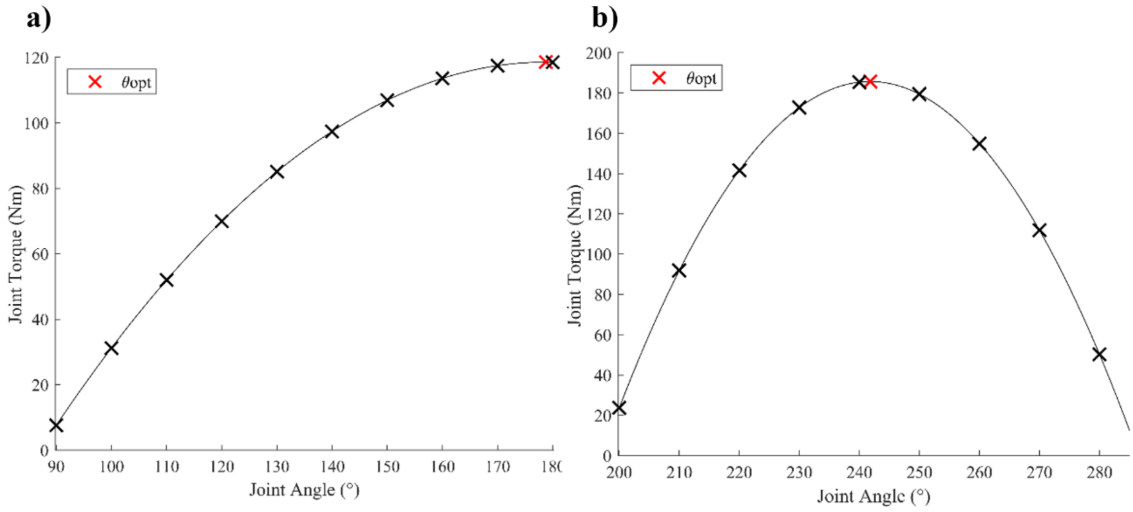

Figure 5.2 Measurement angles were identified at 10° intervals throughout the 'original' joint torque-angle profile for a) knee flexion (posterior joint angle: 90-180°) and b) knee extension (anterior joint angle 200-285°)

The effect of the number and location of measurement angle for each torque-angle dataset was investigated for all possible measurement combinations using a minimum of three measurement angle up to the maximum available in the joint range (knee flexion: 10; knee extension: 9). For each measurement combination, a quadratic joint torque-angle profile was determined using simulated annealing (Corana et al., 1987) to vary the joint torque-angle parameters (peak isometric torque, optimal angle and width) and minimise a cost function. The cost function was defined as the standard unweighted root mean square (RMS) difference between the fitted torque-angle profile and raw torque-angle data (see Section 4.7.4, Equation 4). Parameter values reported by King et al., (2012) served as the initial parameter estimates, with upper and lower bounds taken from the same source (**Table 5.1**). The average RMS difference between original and fitted torque-angle parameters (as a percentage of the original value) across combinations was calculated for each number of measurement angles (3 to 9/10) and referred to as 'parameter error'.

5.3.4 Aim 3: Predicting torque-angle characteristics from experimental data

To address the third aim, maximal voluntary isometric contractions (MVIC) of the knee flexors and knee extensors were measured for a single participant (male university hockey player, age: 21 years, mass: 85 kg, height: 1.805 m) with experience of isokinetic dynamometry testing. The participant was injury-free at the time of testing, had no musculoskeletal injury for the previous 6 months, and had no underlying neurological injury or condition (see Section 4.3). Written informed consent was provided by the participant and ethical approval was granted by the NTU Human Invasive Ethics Committee (ID: 1535801, version 1.0, dated: 19/07/2022).

On arrival to the lab, the participant completed a standardised warm-up on a cycle ergometer for five minutes at a self-selected speed before being seated on a Humac NORM isokinetic dynamometer (CSMi, Stoughton, MA, USA) according to manufacturer guidelines for knee flexion/extension testing. The participant was securely strapped to the chair to limit any undesired movement and instructed to hold (but not apply force to) the handlebars during maximal effort contractions. Care was taken to align the lateral femoral epicondyle with the crank axis under submaximal load with the joint near the optimal angle for the tested joint action (i.e., close to full extension for the knee flexors and near the middle of the joint range for the knee extensors) to limit any angular differences between joint and crank angles. The knee flexors on the dominant side were tested first, followed by the non-dominant side, before repeating the process for the knee extensors. A thorough description of the procedures can be found in the General Methodology (Section 4.7).

Passive torques resulting from passive structures and the weight of the limb and dynamometer attachments were determined from three controlled passive motion trials throughout the participants joint range of motion. A warmup of three concentric-eccentric contractions at $50°\cdot s^{-1}$ followed by 60 s of rest was then completed before a submaximal practice trial at three isometric joint angles (40°, 60°, 80°).

The participant performed knee flexion and knee extension MVICs at five randomised joint angles (20°, 40°, 60°, 80° and 90/100° depending on their available joint range of motion, where 0° = anatomical zero). A selective protocol was adopted to reduce time demands associated with data collection and analyses and was deemed appropriate considering preliminary findings from Aim 2 (presented below). During contractions, the knee joint angle was measured manually using a standard goniometer aligned with the lateral femoral epicondyle. Each contraction lasted 5 s and was performed once at each joint angle, followed by 60 s of rest. Encouragement and visual feedback were provided throughout the trial and two-minutes of rest was permitted during changes between limbs (dominant to non-dominant) and joint actions (knee flexion to knee extension).

Torque and angle data were extracted unfiltered and unsmoothed for methodological consistency and to reduce the influence of smoothing techniques on study findings. The resulting data consisted of maximum voluntary isometric knee flexor and knee extensor joint torque for five joint angles on the right and left limb. These data were used to describe the relationship between torque production and joint angle in a monoarticular representation of the knee joint using a three-parameter quadratic function (Equation 3). The maximum measured torque across the tested joint angles for each limb and joint action were identified as measured peak torque (PT_m).

The effect of the number and location of measurement angles on predicted peak torque (T_0) was investigated for all possible measurement combinations using three, four and five measurement angles in each torque-angle dataset. For each measurement combination, subject specific parameter values were determined using simulated annealing (Corana et al., 1987) to minimise a cost function. The cost function was defined as the weighted root mean square (wRMS) difference between the fitted torque-angle profile and measured torque-angle data (Equation 4). Initial parameter estimates were obtained from the measured data and literature sources and given upper and lower bounds based on physiologically realistic values (**Table 5.4**, **Table 5.6**). A weighting of 100 was given to data points where the measured torque > the function value ($w_1 = 100$), and a weighting of 1 was given to data points where the raw torque < the function value ($w_2 = 1$). Using a weighted RMS difference resulted in a function that better represented simulated maximum joint torque (i.e., smaller differences between measured and optimised peak torque) by minimising the influence of submaximal measurements made within the joint range (see Section 4.7.4). The average wRMS difference between original and fitted torques (as a percentage of PT_m) across combinations was calculated for each number of measurement angles (3/4/5). The difference between optimised and measured peak torque (as a percentage of PT_m) was calculated for each measurement combination and referred to as 'peak torque error'. The RMS of peak torque error was then calculated for each number of measurement angles (3/4/5) to give an indication of model performance across combinations.

5.4 Results

5.4.1 Aim 1: The effect of joint angle location in a single measurement angle, isokinetic dynamometry approach to assess peak torque

4.1.1.1 Knee Flexion

The smallest mean torque error was observed at a measurement angle of 150° (2.4 ± 2.8%; **Table 5.2**; **Figure 5.3c**), with 0% torque error for every width variation (half range: 92-112°) when the optimal angle was 150° (**Table 5.2**; **Figure 5.3a-c**). The largest mean torque error was observed at a measurement angle of 90° (50.0 ± 18.1%; **Table 5.2**; **Figure 5.3a**), with 96.2% torque error when the half range and optimal angle were 92° and 90°, respectively (**Table 5.2**; **Figure 5.3a-c**). This highlights torque error increases as the measurement angle is displaced further from the optimal angle, particularly for narrower joint torque-angle profiles with smaller half ranges.

Table 5.2 Torque error (joint torque at measurement angle vs peak isometric torque) for commonly tested joint angles across a series of 'individual' joint torque-angle profiles for the knee flexors (*N* = 294) and knee extensors (*N* = 935)

Joint Action	Joint Angle (°)	Torque Error (%)			
		Mean ± SD	Minimum	Maximum	Range
Knee Flexion	90	50.0 ± 18.1	19.8	96.2	76.4
	120	17.3 ± 10.0	3.2	42.8	39.6
	150	2.4 ± 2.8	0.0	10.7	10.7
Knee Extension	230	5.2 ± 5.1	0.0	20.0	20.0
	240	1.5 ± 1.4	0.0	5.0	5.0
	270	34.9 ± 16.1	9.8	79.9	70.2

*Joint angle definitions: knee flexion (posterior), knee extension (anterior)

4.1.1.2 Knee Extension

The smallest torque error was observed at a measurement angle of 240° (1.5 ± 1.4%; **Table 5.2**; **Figure 5.3e**), with 0% torque error for every width variation (half range: 45-64°) when the optimal angle was 240° (**Table 5.2**; **Figure 5.3d-f**). The largest torque error was observed at a measurement angle of 270° (34.9 ± 16.1%; **Table 5.2**; **Figure 5.3d**), with 79.9% torque error when the half range and optimal angle were 45° and 230°, respectively (**Table 5.2**; **Figure 5.3d-f**). This highlights, again, torque error increases as the measurement angle is displaced further from the optimal angle, particularly for narrower joint torque-angle profiles with smaller half ranges.

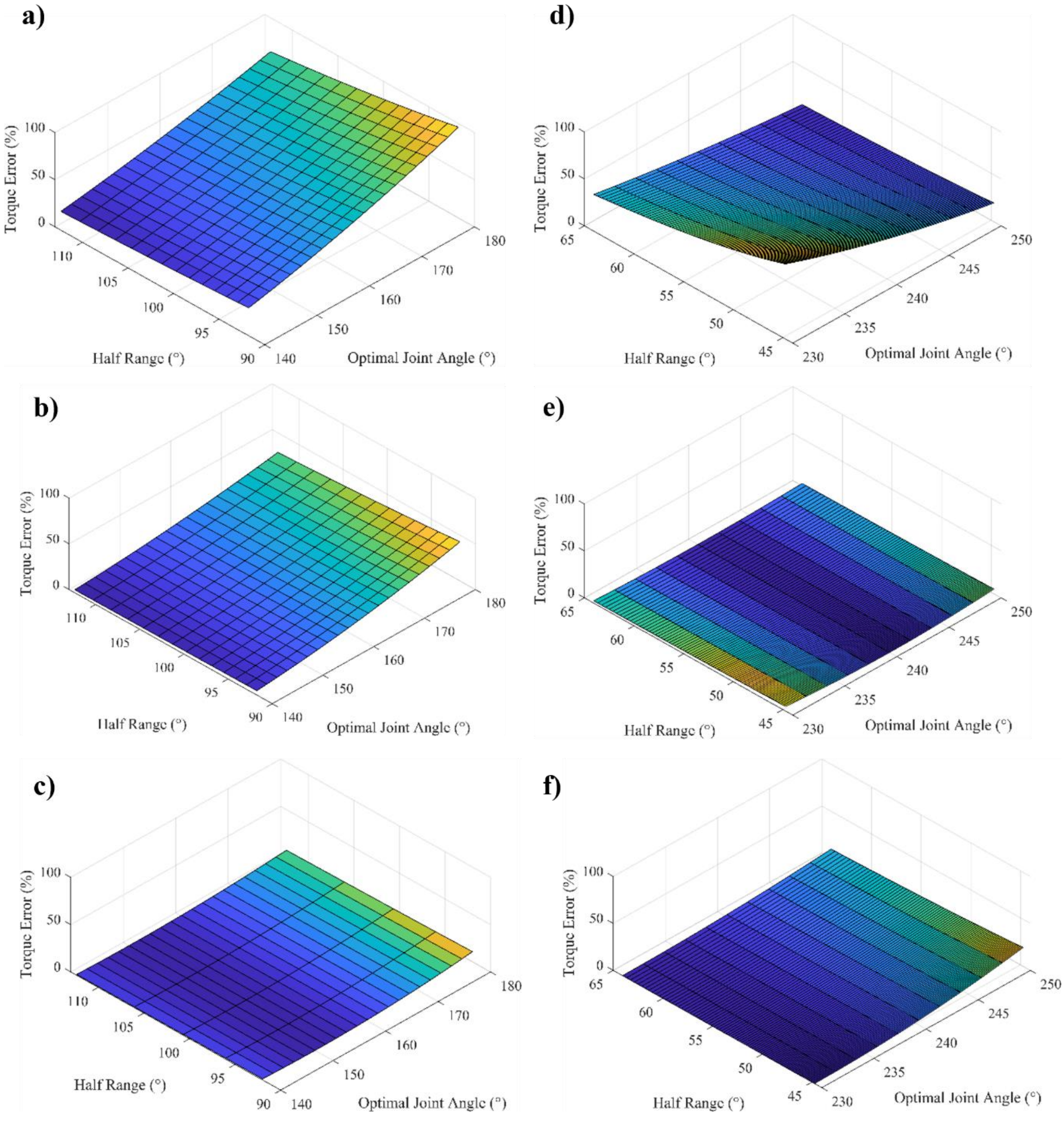

Figure 5.3 Torque error (joint torque at measurement angle vs peak isometric torque) for a series of knee flexion torque-angle profiles ($N = 294$) measured at a) 90°, b) 120° and c) 150° (posterior joint angles) and knee extension torque-angle profiles ($N = 935$) measured at d) 270°, e) 240° and f) 230° (anterior joint angles)

5.4.2 Aim 2: The effect of joint angle number and location in a multiple measurement angle, curve fitting approach to predict torque-angle characteristics

5.4.2.1 Knee Flexion

The smallest parameter errors between the original and fitted joint torque-angle profiles were observed when nine measurement angles were used to predict torque-angle characteristics (T_0 = 4.3%, θ_{opt} = 4.1%, k_2 = 17%; **Table 5.3**). As the number of measurement angles increased from three to the maximum available in the joint range *(N* = 10), mean parameter errors decreased by 2.5%, 4.6%, 61%, for peak torque, the optimal angle and width, respectively (**Table 5.3**). When the number of measurement angles increased from nine to ten; however, mean parameter errors increased by 0.4%, 0.5% and 0.5%, for peak torque, the optimal angle and width, respectively (**Table 5.3**).

Smaller parameter errors were observed when predicting parameters from combinations that included at least one measurement angle near the optimal angle (170° or 180°) as well as an additional flexed or mid-range angle (Appendix 4, **Table A4.1**). For example, measuring at 100°, 130° and 180° resulted in relatively low parameter errors in peak torque, the optimal angle and width of 4.6%, 4.8% and 18.4%, respectively. Combinations consisting of consecutive measurement angles near to the optimal angle, e.g., [160°, 170°, 180°] resulted in relatively small errors in peak torque (3.8%) and the optimal angle (5.9%), but larger errors in the width (131.7%).

5.4.2.2 Knee Extension

The smallest parameter errors between the original and fitted joint torque-angle profiles were observed when eight measurement angles were used to predict torque-angle characteristics (T_0= 2.8%, θ_{opt}= 0.1% and k_2= 2.7%; **Table 5.3**). As the number of measurement angles increased from three to the maximum available in the joint range *(N* = 9), mean parameter errors decreased by 1.4%, 1.1% and 9.1%, for peak torque, the optimal angle and width, respectively (**Table 5.3**). When the number of measurement angles increased from eight to nine; however, mean parameter errors for peak torque and width increased by 0.1% and 0.6%, respectively (**Table 5.3**).

Smaller parameter errors were observed when predicting parameters from combinations that included at least one measurement angle near the optimal angle (240° or 250°) as well as a measurement angle on both the ascending and descending limb of the curve (Appendix 4, **Table A4.2**). For example, measuring at 200°, 240° and 280° resulted in relatively low parameter errors of 3.1%, 0.1% and 2.6%, for peak torque, the optimal angle and width, respectively. Combinations consisting of consecutive measurement angles near to the optimal angle, e.g., [230°, 240°, 250°] resulted in small errors in peak torque (3.3%) but relatively large errors for the optimal angle (2.8%) and width (34.9%). Larger errors were also observed for combinations which included only ascending or descending measurement angles, e.g., [200°, 210°, 220°] or [260°, 270°, 280°].

Table 5.3 Mean ± SD (min-max) parameter error (%) between 'original' and 'predicted' parameter values across measurement combinations (N)

	Number of							
	3 KF: N = 120 KE: N = 84	**4** KF: N = 210 KE: N = 126	**5** KF: N = 252 KE: N = 126	**6** KF: N = 210 KE: N = 84	**7** KF: N = 120 KE: N = 36	**8** KF: N = 45 KE: N = 9	**9** KF: N = 10 KE: N = 1	**10** KF: N = 1
Knee Flexion								
T_0	7.2 ± 3.2 (3.1 - 13.7)	6.0 ± 2.6 (3.33 – 13.93)	5.4 ± 1.8 (3.53 – 13.32)	4.9 ± 1.2 (3.52 – 11.16)	4.7 ± 0.8 (3.82 – 9.05)	4.5 ± 0.6 (3.89 – 6.76)	4.3 ± 0.4 (3.88 – 5.03)	4.7
θ_{opt}	9.2 ± 2.0 (4.8 – 16.0)	7.3 ± 1.7 (3.86 – 11.46)	6.1 ± 1.5 (3.12 – 9.93)	5.3 ± 1.2 (3.27 – 9.13)	4.8 ± 0.9 (3.34 – 7.68)	4.5 ± 0.6 (3.33 – 6.19)	4.1 ± 0.5 (3.63 – 5.45)	4.6
k_2	78.4 ± 47.6 (18.4 – 224.7)	41.9 ± 21.3 (17.2 – 133.1)	29.5 ± 11.2 (15.2 – 80.7)	23.5 ± 7.0 (14.3 – 59.8)	20.2 ± 4.6 (14.2 – 38.0)	18.3 ± 2.8 (14.6 – 28.2)	17.0 ± 1.6 (15.5 – 20.6)	17.5
hR	24.1 ± 5.8 (10.3 – 37.6)	17.5 ± 4.7 (8.4 – 31.0)	13.9 ± 3.7 (7.7 – 25.2)	11.7 ± 2.9 (7.0 – 23.9)	10.3 ± 2.0 (7.0 – 16.7)	9.5 ± 1.4 (7.3 – 13.1)	8.6 ± 0.9 (7.8 – 11.1)	9.4
Knee Extension								
T_0	4.3 ± 1.5 (2.3 – 9.6)	3.3 ± 0.7 (2.3 – 6.5)	3.1 ± 0.4 (2.2 – 4.6)	3.0 ± 0.3 (2.4 – 3.7)	3.0 ± 0.2 (2.5 – 3.6)	2.8 ± 0.2 (2.6 – 3.1)	2.9	-
θ_{opt}	1.2 ± 1.4 (0.1 – 6.2)	0.4 ± 0.6 (0.1 – 2.7)	0.2 ± 0.2 (0.1 – 1.5)	0.1 ± 0.1 (0.1 – 0.5)	0.1 ± 0.0 (0.1 – 0.2)	0.1 ± 0.0 (0.1 – 0.1)	0.1	-
k_2	12.4 ± 10.2 (2.4 – 47.1)	6.1 ± 4.7 (2.2 – 25.1)	4.0 ± 1.9 (2.2 – 14.1)	3.3 ± 0.9 (2.3 – 4.5)	3.0 ± 0.6 (2.3 – 4.5)	2.7 ± 0.4 (2.3 – 3.6)	3.3	-
hR	9.5 ± 11.7 (1.2 – 62.8)	3.5 ± 3.8 (1.1 – 22.7)	2.0 ± 1.1 (1.1 – 9.0)	1.6 ± 0.5 (1.1 – 3.5)	1.4 ± 0.3 (1.1 – 2.2)	1.3 ± 0.2 (1.1 – 1.7)	1.6	-

KF = knee flexion; KE = knee extension; T_0 = peak isometric torque (Nm); θ_{opt} = optimal angle for T_0 (°); k_2 = width of torque-angle profile, hR = half range (distance from θ_{opt} to quadratic root in degrees)

5.4.3 Aim 3: Predicting torque-angle characteristics from experimental data

5.4.3.1 Knee Flexion

The calculated subject-specific parameters for knee flexion torque (**Table 5.4**) closely represented the measured data, with wRMS differences between measured and fitted torques across all measurement combinations and both limbs ranging from 0.8 Nm to 2.8 Nm (0.5% to 1.4% of PT_m; **Table 5.5**). Torque measurements that were larger than the calculated torques had a mean difference of 0.2 Nm to 1.2 Nm, whilst torque measurements that were less than the calculated torques had a mean difference of 7.3 Nm to 18.6 Nm. The most accurate representations for the right limb were observed when using three measurement angles which exhibited a wRMS difference of 2.1 Nm (1.1% of PT_m). The differences between calculated and measured torques on the right limb were larger for the representations derived from four or five measurement angles, with differences of 1.1% and 1.4% of PT_m, respectively. The most accurate representations for the left limb were observed when using five measurement angles which exhibited a wRMS difference of 0.8 Nm (0.5% of PT_m). The differences between calculated and measured torques on the left limb were larger for the representations derived from three and four measurement angles, with differences of 0.6% and 1.0% of PT_m, respectively.

Table 5.4 Knee flexion model parameters (mean ± SD) across measurement combinations (*N*) for three, four and five measurement angles on the right and left limb

	Right			**Left**			**Bounds (LB; UB)**
	3 (*N* = 10)	**4 (*N* = 5)**	**5 (*N* = 1)**	**3 (*N* = 10)**	**4 (*N* = 5)**	**5 (*N* = 1)**	
PT_m (Nm)	178.3 (± 19.69)	186.22 (± 16.23)	193.48	153.79 (± 19.05)	161.6 (± 8.19)	165.26	/
T_0 (Nm)	205.45 (± 7.12)	204.14 (± 5.57)	209.44	175.6 (± 4.25)	173.47 (± 4.78)	175.34	±10% of PT_m
θ_{opt} (°)	138.71 (± 10.09)	134.59 (± 3.92)	131.78	137.41 (± 9.5)	133.46 (± 3.75)	133.41	131.78; 206.26
k_2	0.55 (± 0.17)	0.6 (± 0.15)	0.71	0.61 (± 0.14)	0.67 (± 0.09)	0.69	0.2; 2.0
hR (°)	80.13 (± 14.9)	75.53 (± 10.22)	67.81	75.6 (± 12.63)	70.2 (± 5.19)	69.06	/

PT_m = measured peak isometric torque, T_0 = optimised peak isometric torque, θ_{opt} = optimal angle (posterior) for T_0, k_2 = width of torque-angle profile, hR = distance from θ_{opt} to the quadratic root of torque-angle profile

Peak torque error between measured and calculated peak torque across all combinations and both limbs ranged from 9.3 to 16.0 Nm (5.6% to 8.3%; **Table 5.5**). The smallest peak torque errors for both limbs were observed when using four measurement angles, with differences between measured and calculated peak torque on the right and left limb of 11.8 Nm (6.1%) and 9.3 Nm (5.6%), respectively. The differences between measured and calculated peak torque were larger for representations derived from three and five measurement angles, with differences on the right limb of 7.1% and 8.3%, respectively and differences on the left limb of 6.7% and 6.1%, respectively.

Table 5.5 Knee flexion model performance across measurement combinations (*N*) for three, four and five measurement angles on the right and left limb

Output	Description	Right			Left		
		3 (*N = 10*)	**4 (*N* = 5)**	**5 (*N* = 1)**	**3 (*N = 10*)**	**4 (*N* = 5)**	**5 (*N* = 1)**
wRMS (%) [mean ± sd]	Weighted RMS difference between measured and fitted torques (% of PT_m)	1.09 ± 0.79	1.12 ± 0.28	1.42	0.62 ± 0.54	0.99 ± 0.68	0.47
Peak torque error (%) [RMS; Min; Max]	Difference between measured and T_0 (% of PT_m)	7.1 (-0.47;9.72)	6.08 (2.54;8.75)	8.25	6.71 (0.42;9.65)	5.6 (1.85;9.64)	6.1

RMS = root mean square, PT_m = measured peak isometric torque, T_0 = optimised peak isometric torque

5.4.3.2 Knee Extension

The calculated subject-specific parameters for knee extension torque (**Table 5.6**) closely represented the measured data, with wRMS differences between measured and fitted torques across all measurement combinations and both limbs ranging from 1.5 Nm to 5.0 Nm (0.6% to 2.1% of PT_m; **Table 5.7**). Torque measurements that were larger than the calculated torques had a mean difference of 0.3 Nm to 1.9 Nm, whilst torque measurements that were less than the calculated torques had a mean difference of 13.8 Nm to 36.6 Nm. The most accurate representations for both limbs were observed when using three measurement angles which exhibited wRMS differences on the right and left limb of 1.5 Nm (0.6% of PT_m) and 2.0 Nm (0.8% of PT_m), respectively. The differences between measured and calculated torques were larger for representations derived from four and five measurement angles, with differences on the right limb of 2.0% and 2.1%, respectively and differences on the left limb of 1.5% and 1.5% of PT_m, respectively.

Table 5.6 Knee extension model parameters (mean ± SD) across measurement combinations (*N*) for three, four and five measurement angles on the right and left limb

	Right			Left			Bounds (LB; UB)
	3 (*N = 10*)	**4 (*N = 5*)**	**5 (*N = 1*)**	**3 (*N = 10*)**	**4 (*N = 5*)**	**5 (*N = 1*)**	
PT_m (Nm)	227.03 (± 24.5)	237.06 (± 19.5)	245.78	228.93 (± 10.53)	233.35 (± 5.5)	235.82	/
T_0 (Nm)	240.1 (± 15.9)	245.43 (± 15.06)	258.89	233.3 (± 10.34)	235.73 (± 8.51)	234.47	±10% of PT_m
θ_{opt} (°)	235.35 (± 10.46)	231.84 (± 6.80)	4.07 233.31	225.14 (± 8.94)	219.58 (± 5.11)	226.15	177.62; 315.13
k_2	0.64 (± 0.47)	0.53 (± 0.31)	0.57	0.43 (± 0.34)	0.25 (± 0.09)	0.2	0.2; 2.0
hR (°)	81.94 (± 23.61)	87.7 (± 26.86)	1.32 (75.59)	101.48 (± 28.56)	117.55 (± 17.01)	127.47	/

PT_m = measured peak isometric torque, T_0 = optimised peak isometric torque, θ_{opt} = optimal angle (anterior) for T_0, k_2 = width of torque-angle profile, hR = distance from θ_{opt} to the quadratic root of torque-angle profile

Peak torque error between measured and calculated peak torque across all combinations and both limbs ranged from -1.4 Nm to 16.1 Nm (-0.6% to 6.6%; **Table 5.7**). The smallest peak torque errors for both limbs were observed when using five measurement angles, with differences between measured and calculated peak torque on the right and left limb of 13.1 Nm (5.3%) and -1.35 Nm (-0.6%), respectively. The differences between measured and calculated peak torque were larger for representations derived from three and four measurement angles, with differences on the right limb of 6.6% and 5.5%, respectively and differences on the left limb of 4.3% and 3.2%, respectively.

Table 5.7 Knee extension model performance across measurement combinations (*N*) for three, four and five measurement angles on the right and left limb

Output	Description	Right			Left		
		3 (*N = 10*)	**4 (*N = 5*)**	**5 (*N* = 1)**	**3 (*N* = 10)**	**4 (*N = 5*)**	**5 (*N* = 1)**
wRMS (%) [mean ± sd]	Weighted RMS difference between measured and fitted torques (% of PT_m)	0.63 ± 0.46	1.95 ± 0.68	2.05	0.83 ± 0.73	1.5 ± 0.74	1.45
Peak torque error (%) [RMS; Min; Max]	Difference between measured and T_0 (% of PT_m)	6.56 (-9.85;6.52)	5.48 (-8.18;9.03)	5.33	4.29 (-9.58;5.32)	3.23 (-3.95;4.56)	-0.57

PT_m = measured peak isometric torque, T_0 = optimised peak isometric torque

5.5 Discussion

This study demonstrates the effect of utilising single and multiple measurement angle approaches to determine isometric torque-angle characteristics from isokinetic dynamometry data. Protocols with a single measurement angle were shown to underestimate peak joint torque when assessed at commonly tested angles, with potential errors of 96.2% and 79.9% observed at the most common measurement angle (90°) for the knee flexors and knee extensors, respectively. For multiple measurement angle approaches, parameter errors reduced as the number of measurement angles increased and more accurate parameter predictions were found for combinations that included measurement angles spread throughout the joint range and at least one close to the optimal angle. Joint torque-angle profiles for the knee flexors and knee extensors were represented well by the selective approaches using three to five measurement angles, with RMS differences between measured and fitted torques of 0.5-2.1% of maximum measured torque. Torque representations varied with the location of measurement angles, but no observable pattern could be discerned between combinations.

Single measurement angle approaches provided more accurate predictions of peak torque the closer the measurement angle was to the optimal angle, with 0% torque error when the measurement angle and optimal angle coincided (**Table 5.2**). Measurement protocols that use a single measurement angle are not uncommon in the literature (Bampouras et al., 2017; Blazevich et al., 2009a; Bojsen-Møller et al., 2005; Hori et al., 2020) and are often implemented when time constraints limit a more thorough approach. This research found the smallest mean torque errors occurred at 150° for knee flexion (2.4 ± 2.8%) and 240° for knee extension (1.5 ± 1.4%), while the largest torque errors occurred at 90° for knee flexion (50.0 ± 18.1%) and 270° for knee extension (34.9 ± 16.1%; **Table 5.2**). These findings align with the optimal angle of the knee joint torque-angle profiles, therefore, if a single measurement angle approach is necessary, joint angles near to 150° for the knee flexors and 240° for the knee extensors are recommended (Brughelli et al., 2010; de Sousa et al., 2023; Kellis & Blazevich, 2022; Marginson & Eston, 2001; Mohamed et al., 2002; Pincivero et al., 2004). Nevertheless, protocols with a single measurement angle are still prone to underestimations if the measurement angle and optimal angle are displaced from one another. This is a particular concern given the individual- and muscle-specific nature of the torque-angle profile (Brughelli et al., 2010; Frasson et al., 2007; Herzog et al., 1990; Herzog & ter Keurs, 1988b; Kellis & Blazevich, 2022; Kulig et al., 1984; Savelberg &

Meijer, 2003), and the prevalence of torque measurements at 90° knee flexion. Researchers and practitioners should, therefore, remain cautious when implementing and interpreting joint torques from single measurement angle approaches, especially when using them to compare between individuals, as the difference between peak isometric torque and that which is measured can be extreme.

Variations in half range between 92-112° and 45-64° were observed for the knee flexors and knee extensors, respectively. These variations created increasingly narrow torque-angle profiles, particularly for the knee extensors, which typically display an ascending-descending profile within the anatomical limits of the joint (Kulig et al., 1984). Predictably, half range variations had no effect on measured peak torque when the measurement angle and optimal angle coincided. When the measurement angle and optimal angle did not coincide, however, torque error increased as the half range decreased and the torque-angle profile narrowed. Larger errors may, therefore, be expected when measuring torque from the knee extensors as the drop off from peak torque is steeper due to their narrow profile. Seemingly, this contradicts the findings of the current study, as larger torque errors were observed for knee flexion than for knee extension. Yet, this can be explained in relation to the distance of the optimal angle to the measurement angle which, at the most displaced joint angle, was a maximum of 90° for the knee flexors compared to 40° for the knee extensors. As such, particular care should be taken when measuring torque from narrower joint torque-angle profiles, as the scope for error is more extreme when measurements are made at suboptimal joint angles.

Multiple measurement angle approaches provided more accurate predictions of joint torque-angle characteristics, as the number of measurement angles increased (**Table 5.3**). Although measurement approaches using 6-8 measurement angles have been detailed previously in the modelling literature (Anderson et al., 2007; Conceição et al., 2012; Forrester et al., 2011; King et al., 2012; Lewis et al., 2012, 2018, 2021), the effect of these multiple measurement approaches has not been investigated. The findings of this study indicate improved parameter predictions from approaches with more measurement angles as more information about the shape of the profile is provided. Larger parameter errors were observed when fewer measurement angles were used, particularly for the knee flexors, which typically display flatter joint torque-angle profiles than the knee extensors (Kulig et al., 1984). As a result, the difference in joint torque between consecutive measurements near the optimal angle is smaller and the turning point becomes harder to discern, leading to less accurate predictions particularly for the width and half range parameter values. Parameter errors were, however, reduced for measurement combinations that included a spread of measurement angles throughout the joint range and at least one measurement angle near the optimal angle. Experimental protocols that adopt this strategy are, therefore, recommended when predicting torque-angle characteristics, particularly when using fewer measurement angles for largely ascending and flat torque-angle profiles. Yet, if the primary research objective is to determine peak torque at the optimal angle, and not the whole torque-angle profile, the effect of measurement protocol on width predictions may be of less consequence.

Joint torque-angle profiles for both the knee flexors and knee extensors were represented well by the experimental approach, which utilised voluntary isometric torque at three to five angles throughout the joint range of motion. Small differences were observed between measured and fitted torques (≤ 2.1% of maximum measured torque; **Table 5.5**; **Table 5.7**) which suggests a selective measurement approach may be used to accurately represent measured torques. This is particularly useful for scenarios where extensive protocols are not feasible due to limited time and financial resources. Notably, larger RMS differences were observed as the number of measurement angles increased above three, indicating the function more closely represented experimental data using fewer measurement angles. A closer fit would, however, be undesirable for the current dataset due to the presence of submaximal torque measurements (approximately 10% of maximum measured torque). The weighting approach aimed to reduce the influence of submaximal torque measurements on the function by giving a higher weighting to calculated torques that were larger than the measured torques. Resultantly, the likelihood and magnitude of underestimations in calculated peak torque was reduced, particularly for protocols with more measurement angles (**Table 5.5**; **Table 5.7**). Measured peak isometric torque also increased as the number of measurement angles increased from three to five, resulting in a mean increase of 14-15 Nm for the knee flexors and 7-19 Nm for the knee extensors, and subsequently larger calculated peak torques. Protocols with fewer measurement angles, on the other hand, were prone to larger underestimations in calculated and measured peak torques, especially for measurement combinations that included more suboptimal joint angles and submaximal torques. Optimised parameter values also varied between measurement approaches, with larger peak isometric torques generally observed with increasing the number of measurement angles (**Table 5.4**; **Table**

5.6). The knee flexors exhibited smaller optimal angles (i.e., shorter muscle lengths) and larger widths (i.e., smaller half ranges) when using five measurement angles, producing taller, narrower torque-angle profiles. Meanwhile, the knee extensors exhibited smaller optimal angles (i.e., shorter muscle lengths) and smaller widths (i.e., larger half ranges) when using five measurement angles, producing taller but wider torque-angle profiles. Thus, measurement protocols with fewer measurement angles are more likely to underestimate maximum strength determined by peak torque. In addition, the knee flexors would be prone to overestimations in angle-specific joint torque at suboptimal angles (due to wider profiles) whereas, the knee extensors would be prone to underestimations (due to narrower profiles) which should be considered when predicting specific torque-angle characteristics.

The data simulation approach adopted for the first two aims of this study has advantages to purely experimental methods which are subject to measurement errors caused by axis misalignment, learning effects, gravity correction and more (Appen & Duncan, 1986; Arampatzis et al., 2004, 2005; Baltzopoulos et al., 1991; Dirnberger et al., 2012; Nugent et al., 2015; Winter et al., 1981). This does, however, require consideration when interpreting our findings in relation to experimental results in the wider literature. In particular, the errors associated with the measurement approaches investigated by data simulation methods are likely to differ when assessed using experimental data. Specifically, experimental data is subject to suboptimal variability and systematic noise of varying degrees depending on the experimental conditions. The experimental data collected for the third aim of this study exhibited submaximal torque measurements up to approximately 10% (of maximum measured torque) which influenced the performance of the model for the measurement approaches (see Section 4.7.4). Submaximal noise would vary by investigation and so researchers should aim to minimise and quantify the noise within their own data before implementing similar curve-fitting techniques. It should also be noted that to address the first aim of the research, parameter perturbations for the optimal angle were constrained, as per the identified articles, to between 140-180° for knee flexion and 230-250° for knee extension. Whilst this is likely to cover an array of normative knee joint torque-angle profiles, it fails to consider the effect of measuring peak torque characteristics across more diverse torque-angle profiles. In addition, the monoarticular quadratic representation of the joint torque-angle relationship in this study ignores the fact that peak knee torque production is biarticular i.e. a function of both the hip, knee and ankle angle (King et al., 2012; Lewis et al., 2012, 2018; Li et al., 2002). However, a monoarticular function has been shown to better represent knee flexor torque than a biarticular function when a flexed hip position is used (King et al., 2012). Furthermore, the contribution of the gastrocnemius to knee flexor torque can be negligible when the ankle is left free if there is limited activation of the dorsiflexors (King et al., 2012). Nonetheless, the errors reported in the present study are likely to vary in response to changes in the hip and ankle joint angles, particularly when measuring knee flexion torque since the biarticular muscle contribution to net torque is larger. Future research, therefore, could investigate the effect of hip and ankle joint angles on the accuracy of knee joint torque-angle profiles from both single and multiple measurement angle approaches.

5.6 Conclusion

Although the isokinetic dynamometer is widely considered as the gold-standard for measuring strength and strength-based indexes, an optimal measurement protocol is necessary to ensure accurate measurements are made. Single measurement angle approaches can result in gross underestimations in isometric peak torque, particularly for narrower torque-angle curves. Alternatively, a curve fitting approach which utilises measurements at multiple joint angles throughout the joint range may offer an effective solution, with more accurate parameter predictions expected from protocols with more measurement angles. To reduce time demands and improve feasibility, protocols with fewer measurement angles can be optimised by including a spread of measurement angles throughout the joint range, including an angle close to the optimum. Variability in the effect of measurement protocol between joint actions were observed, however, which indicates sensitivity to the shape of the torque-angle profile. A selective experimental approach with five measurement angles may be recommended for the prediction of isometric joint torque-angle characteristics of the knee flexors and knee extensors. Yet, the research question, muscle group under investigation, and practical constraints should be carefully considered when formulating an experimental protocol using isokinetic dynamometry.

Chapter 6: Strength and Inter-Limb Asymmetry: Reliability of Functional Tests and Relationships with Isokinetic Dynamometry

6.1 Rationale

Isokinetic dynamometry is recognised as the gold-standard method for measuring muscular strength, and thereby strength asymmetry, yet its use in applied practice is limited due to its association with extensive experimental protocols. The previous chapter demonstrates the effect of single and multiple measurement angle approaches on the assessment of isometric knee strength using dynamometry, indicating protocols with more measurement angles exhibit improved predictions of torque-angle characteristics, including peak torque. In lieu of the time and financial demands associated with extensive dynamometry protocols, more selective protocols with fewer measurement angles can, however, be implemented if the location of measurement angles is optimised. The systematic review in Chapter 3 also demonstrated widespread use of field-based alternatives to isokinetic dynamometry ($N = 42$), including multi-joint strength tests, and jumping/ hopping, for the assessment of functional strength and inter-limb asymmetry. Reliability investigations using functional tests have, however, demonstrated population-, test- and metric- sensitivity, such that further investigation is warranted. The relationships between maximum strength measured by dynamometry and functional strength measured via field-based alternatives should also be appropriately interrogated to establish the utility of functional tests for the purpose of measuring strength and inter-limb asymmetry. Therefore, the aim of this study was firstly, to investigate the within-session test-retest reliability of a battery of unilateral functional strength tests. The second purpose was to assess the relationships between maximum isometric strength and asymmetry determined by dynamometry, and functional strength and asymmetry determined by field-based tests. The dynamometry measurement approach adopts methods discussed in the previous chapter to establish the use of an optimised protocol with three to five measurement angles.

6.2 Introduction

Inter-limb asymmetry, referring to an imbalance in performance or function between sides, has been documented across a range of physical qualities, tests and metrics (Barrera-Domínguez et al., 2021; Batista et al., 2019; Bishop et al., 2017, 2022a, 2023; Chapelle et al., 2021; Exell et al., 2017). Imbalances in strength-based tasks have been identified as a potential risk factor for injury (Brumitt et al., 2020; Croisier et al., 2008; Fort-Vanmeerhaeghe et al., 2022; Fousekis et al., 2011; MacSweeney et al., 2023; Read et al., 2018; Steidl-Müller et al., 2018) and weaker performance (Bishop et al., 2019a, 2019b, 2021b; Fort-Vanmeerhaeghe et al., 2020; Madruga-Parera et al., 2020, 2021). Consequently, assessment of strength asymmetry has become commonplace in both research and practice for injury prevention and rehabilitation, as well as training specialisation and performance monitoring (Carvalho et al., 2016; Fort-Vanmeerhaeghe et al., 2022; Gonzalo-Skok et al., 2019; Jordan & Bishop, 2023; Jordan et al., 2015; Moreno-Azze et al., 2021; Patterson et al., 2020). However, confusion exists due to disparities regarding asymmetry magnitudes and associated effects reported in the literature. Inconsistent and flawed methodological practices related to terminology, calculation and interpretation of asymmetry scores are partly responsible (Parkinson et al., 2021). Current recommendations highlight the importance of selecting an asymmetry index that reflects the nature of the task (Bishop et al., 2018a) and avoids the limitations associated with selecting a reference limb (Parkinson et al., 2021). Measuring the direction of asymmetry (i.e., how consistently one side is favoured over the other across repeated measures) as well as its magnitude is also recommended to avoid a false impression of consistency in scores over repeated measures (Bishop et al., 2020b, 2020a). Further variability exists due to the highly task-, metric- and subject-specific nature of asymmetry, such that a uniform approach to asymmetry calculation and interpretation is not advised (Bishop et al., 2019c; Dos'Santos et al., 2017c; Read et al., 2021). Given the importance of lower limb strength for movement and performance, it is necessary to investigate strength-based asymmetries across a range of tests to understand potential implications of any selected approach.

Isokinetic dynamometry is considered the gold-standard method for measuring strength due to its high reliability for measuring isometric and isovelocity peak torque *in vivo* (de Araujo Ribeiro Alvares et al., 2015; de Carvalho Froufe Andrade et al., 2013; Impellizzeri et al., 2008; Maffiuletti et al., 2007; Tsiros et al., 2011). Muscular strength and function are assessed on the dynamometer by measuring the capacity of the musculature surrounding a joint to produce joint torque under constant conditions. It also provides a safe and controlled environment for testing under maximal effort conditions, particularly for isometric contractions where the dynamometer resists changes in the crank angle. There is, however, no standardised measurement strategy for the diversity of torque-angle profiles that exist between- and within-individuals (Brughelli et al., 2010; Frasson et al., 2007; Herzog et al., 1990; Herzog & ter Keurs, 1988b; Kellis & Blazevich, 2022; Kulig et al., 1984; Savelberg & Meijer, 2003). Measurements are also subject to gross errors due to lack of familiarisation, joint/crank axis misalignment, and variability in feedback (Arampatzis et al., 2004, 2005; Baltzopoulos et al., 1991; Dirnberger et al., 2012; Nugent et al., 2015; Winter et al., 1981). Joint torque-angle (or force-length) characteristics can, however, be estimated from angle-specific peak torque during maximal voluntary isometric contractions (Conceição et al., 2012; Forrester et al., 2011; King et al., 2012; Lewis et al., 2012), and the influence of submaximal torque measurements on the outcome can be minimised to improve estimates of strength parameters (Forrester et al., 2011). It remains, however, that isokinetic dynamometry is generally impractical in an applied environment due to the need for expensive equipment and technical expertise, and its time-consuming nature such that, alternatives are often necessary.

Field-based strength tests have become commonplace in research and practice as a simple and cost-effective means to assess functional strength and asymmetry across a range of athletic and clinical groups (Brumitt et al., 2013; Ceroni et al., 2012; Gustavsson et al., 2006; Impellizzeri et al., 2007; Phukan et al., 2021). Rehabilitation following ACL reconstruction is commonly assessed using functional performance tests, such as jumping and hopping, with findings showing reduced inter-limb asymmetry between 1- and 5-years post-surgery resulting from declining performance on the non-injured limb (Patterson et al., 2020). Reduced inter-limb asymmetries have also been documented in response to strength training, indicating they could be effective in reducing limb imbalances in jumping and isometric strength, particularly amongst weaker subjects (Bazyler et al., 2014; Gonzalo-Skok et al., 2019). Furthermore, jumping and multi-joint strength tests have demonstrated acceptable relative and absolute reliability both within- and between-sessions, yet variability exists between tests and metrics, indicating some tests may be less reliable than others (Bishop et al., 2019c; Dos'Santos et al., 2018c; Merrigan et al., 2022). Impulse from the isometric squat reportedly demonstrates unacceptable reliability (CV: 10.1-13.7%) when performed unilaterally (Bishop et al., 2019c), despite CVs < 10% in the same metric when the task is performed on two limbs (Bazyler et al., 2015; Hart et al., 2012). Unilateral jumping showed better within- and between-session reliability (≤ 8.1%) but jump height in the unilateral drop jump demonstrated unacceptable reliability (10.1-11.2%) between sessions (Bishop et al., 2019c). Resultantly, the reliability of field-based tests should be established within the research context to ensure appropriate interpretation of meaningful results.

Although the purpose of many field-based tests is to provide a feasible alternative to expensive and laborious lab-based methods, the relationships between functional test metrics and maximal strength remains unclear. Isokinetic knee extensor strength, determined from dynamic, constant-velocity contractions, has demonstrated moderate to strong positive relationships with vertical and horizontal jumping (Augustsson & Thomeé, 2000; English et al., 2006; Greenberger & Paterno, 1995; Negrete & Brophy, 2000; Tsiokanos et al., 2002b; Wilk et al., 1994). Unlike isolated joint testing, however, jump and hop tests require activation of all lower limb muscles and joints. The biarticular hamstrings, rectus femoris and gastrocnemius also enable proximal to distal transfer of energy between the hip, knee and ankle joints (Jacobs et al., 1996; Prilutsky & Zatsiorsky, 1994). which may explain why some results show weak to no relationships with knee strength alone (Östenberg et al., 1998; Tsiokanos et al., 2002b; Wilk et al., 1994). Single-joint isometric testing also show relatively poor relationships with dynamic functional tasks (Requena et al., 2009) which likely reflect additional task differences, such as motor unit activation (Murphy & Wilson, 1996) as well as utilisation of the stretch-shortening cycle (Bailey et al., 2013; Furlong & Harrison, 2014). Stronger correlations have, however, been observed between multi-joint isometric strength assessments and dynamic performance (Bailey et al., 2013; Haff et al., 2005; Kawamori et al., 2006; Mcguigan et al., 2010; Stone et al., 2004; Thomas et al., 2017).

Conflicting results similarly exist between inter-limb asymmetries determined by isokinetic dynamometry compared to those from functional strength tests, such as the back squat, unilateral leg press and vertical and horizontal jumping (Jones & Bampouras, 2010; Newton et al., 2006). Investigations indicate variability in asymmetry magnitude between tests, with inter-limb asymmetries in vertical hopping generally larger than in horizontal hopping and multijoint isometric tasks (Bishop et al., 2021b, 2021a; Kozinc & Šarabon, 2020; McCubbine et al., 2018). The direction of asymmetry also demonstrates inconsistency between tests, with kappa values indicating the favoured limb in one test may not translate across other tests (Bishop et al., 2020a, 2021a; Kozinc & Šarabon, 2020). Therefore, the relationship between isometric strength determined by isokinetic dynamometry and functional performance tests warrants further investigation to establish associations between tests in asymmetry and in performance.

The relationship between asymmetries in functional tests and sport-specific performance has been investigated, with some findings indicating larger asymmetries are associated with weaker athletic performance (Bishop et al., 2019a, 2019b, 2021b; Madruga-Parera et al., 2020, 2021). Bishop et al., (2021b) reported jump height and distance asymmetries in the countermovement jump (CMJ) and triple hop test, respectively were negatively associated with jump performance and 5 m, 10 m and 20 m sprint performance in elite youth female soccer players. The relationship between asymmetry and performance has also been investigated in multi-joint strength tests such as, the IMTP and isometric squat, demonstrating a decline in jump performance and kicking accuracy with increasing asymmetry (Bailey et al., 2013; Hart et al., 2014). However, conflicting evidence exists across the variety of tests adopted, with some reports of no relationship between asymmetry and performance outcomes (Dos'Santos et al., 2018c; Lockie et al., 2014; Raya-González et al., 2020). Lockie et al., (2014) observed asymmetries of 3.3-10.4% in vertical, horizontal and lateral jump tests performed by collegiate athletes, but no significant correlations between asymmetry and sprint or change of direction speed performance for any of the jump tests. Dos'Santos et al., (2018c) also reported no significant correlations between asymmetry in the IMTP and change of direction speed test. Similarly, athletes grouped based on lesser and greater asymmetry in the IMTP did not demonstrate significant differences in change of direction speed performance (Lockie et al., 2014). Thus, investigation of the relationships between inter-limb asymmetries and performance across various strength-based tests is warranted to better inform methodological decisions in research and practice.

Given the potential uses of field-based alternatives to isokinetic dynamometry, the relationship between performance and inter-limb asymmetries in maximal isometric strength and functional strength warrants further discussion. Other tests and metrics, in addition to those mentioned above, also require investigation within the research context to establish their uses and implications for lab- and field-based practices. Therefore, the purpose of this research was to 1) establish within-session reliability of unilateral field-based tests for the assessment of functional strength and its associated asymmetries and 2) investigate the relationships between performance and inter-limb asymmetries in maximal knee flexor/extensor isometric strength and functional strength.

6.3 Methods

6.3.1 Experimental Design

A cross-sectional design was used to investigate maximal isometric strength and functional performance, and their associated asymmetries amongst university-level athletes during the British University & Colleges Sport (BUCS) 2023/24 season. Participants attended the university laboratory three times, for 1) field-based familiarisation (1 hr), 2) field-based testing (2.5 hrs) and 3) isokinetic dynamometry testing (1 hr). The battery of functional strength tests included an IMTP, CMJ and horizontal jump for distance (HJ), all performed unilaterally on the dominant and non-dominant limb. During isokinetic dynamometry testing, participants performed isometric knee flexions and knee extensions at five joint angles throughout the joint range of motion on both limbs. Familiarisation for functional strength testing was completed at least 48 hrs prior to data collection and both testing sessions were completed at approximately the same time of day within a seven-day period during preseason (August 2023).

6.3.2 Participants

Fifteen healthy male hockey athletes (age: 19.7 ± 1.0 years; height: 179.6 ± 4.5 cm; mass: 79.4 ± 8.8 kg) competing within the BUCS League participated in this study. *A priori* power analysis using G*Power (Version 3.1, University of Dusseldorf, Germany) identified 15 participants were required to achieve a statistical power of 0.8 and a type 1 alpha level of 0.05. All participants were injury-free at the time of testing, had a minimum of one year experience in their primary sport and were competing at university level or higher (university, n = 13; international, n = 3; see Section 4.3). Training data for the recruited sample was provided by the coaching team by completion of a training report form (Appendix 3, A3.1). At the time of testing, the athletes were engaged in four sessions per week (⩾ 90 minutes each) and were not currently participating in match play within the BUCS League. The purpose of training was to improve aspects of physical fitness (cardiovascular endurance, muscular strength, muscular endurance, flexibility, body composition). Written informed consent was provided by all participants and ethical approval was granted by the NTU Human Invasive Ethics Committee (ID: 1535801, version 1.0, dated: 19/07/2022).

6.3.3 Procedures

6.3.3.1 Functional Strength Tests

A standardised warm up consisting of jogging, dynamic stretches (e.g., walking lunges, hamstring sweeps, side lunges), sprinting and acceleration/decelerations, followed by jumping and hopping in both vertical and horizontal directions was conducted at the start of each field-based session. During familiarisation, participants were introduced to the testing procedures and were permitted as many practice trials as necessary for each test. The testing procedures (see Section 4.6) were re-introduced to the participants on the second lab visit and additional warm-up trials were permitted before maximal effort testing. Participants were instructed to stand in the centre of the force platform with the free knee flexed to approximately 90°. Three maximal effort trials of each test were conducted separated by one minute of rest between trials, with the CMJ jump performed first followed by the horizontal jump and then the IMTP. To limit learning effects, the order of dominant and non-dominant limb trials was randomised for each individual. Instructions for the task were the same for all participants and consistent feedback was provided to ensure proper technique. All kinetic data were extracted unfiltered and subsequently copied into a custom-made spreadsheet for analysis following published guidance (Chavda et al., 2020; Comfort et al., 2019; McMahon et al., 2018).

Isometric Midthigh Pull

The IMTP was conducted using a portable rig with a uniaxial force plate system (PASPORT force plate, PASCO Scientific, California, USA), sampling at 1000 Hz. Procedures were conducted in line with previous recommendations (Comfort et al., 2019) and are detailed in full in the General Methodology (Section 4.6). Participants were instructed to stand with one foot roughly in the centre of the force plate and to assume a body position that replicates the second pull phase of the power clean. The height of the bar was determined individually for each athlete during familiarisation to ensure optimal joint angles were obtained at the knee and hip (125-145° and 140-150°, respectively, where full joint extension corresponds to 180°). To limit the effect of grip strength, all participants held onto the bar using weight-lifting hooks. Participants first performed two warm-up trials (3 s submaximal pull at 50% and 75% of their perceived maximum effort) followed by three maximal effort trials lasting 5 s, each separated by one minute of rest.

Standardised instructions to "drive your feet into the ground as hard and fast as possible" were given to ensure maximum force and rate of force development during maximal effort trials. Trials with an observable countermovement, excessive pre-tenson or an absent 1 s stable weighing period before the onset of the pull were deemed unsuccessful and repeated after a 60 s rest period. Peak force during the 5 s pull was identified in absolute terms and as relative peak force by dividing net force by body mass ($N{\cdot}kg^{-1}$).

Countermovement Jump

Participants stood on a multiaxial force plate system (AMTI, Watertown, MA, USA) sampling at 1000 Hz, with their hands positioned on the hips. Instructions were to squat down to a self-selected depth, rapidly explode upwards to achieve maximal height and land using a preferred strategy on either one or two limbs. Swinging of the free limb was not permitted and participants were required to keep their hands on the hips and avoid excessive hip or knee flexion during the airborne phase and upon landing. Unsuccessful trials were repeated following a 60 s rest period. Jump height was calculated using the take-off velocity method and peak force was extracted from the propulsive phase before take-off (see Section 4.6.2).

Horizontal Jump

Participants stood on the same force plate system as for the CMJ, with their hands positioned on the hips. Participants were instructed to align the toes directly behind the start line on the force plate, jump as far as possible to achieve maximal distance, and land using their preferred strategy on either one or two limbs. Swinging of the free limb was not permitted and participants were required to keep their hands on hips throughout. Participants were asked to complete additional trials if their jump distance improved by more than 10 cm between trials. Unsuccessful trials were repeated following a 60 s rest period. Jump distance was measured from the start line at take-off to the heel of the first landing foot and resultant peak force was extracted from the propulsive phase before take-off (see Section 4.6.2).

6.3.3.2 Isokinetic Dynamometry

On arrival to the lab, participants completed a standardised warm-up on a cycle ergometer for five minutes at a self-selected speed before being seated on a Humac NORM isokinetic dynamometer (CSMi, Stoughton, MA, USA) according to manufacturer guidelines for knee flexion/extension testing. Participants were securely strapped to the chair to limit any undesired movement and instructed to hold the handlebars during maximal effort contractions. Care was taken to align the lateral femoral epicondyle with the crank axis under submaximal load with the joint near the optimal angle for the tested joint action (i.e., close to full extension for the knee flexors and near the middle of the joint range for the knee extensors) to limit any angular differences between joint and crank angles. The knee flexors on the dominant side were tested first, followed by the non-dominant side, before repeating the process for the knee extensors. A thorough description of the procedures can be found in the General Methodology (Section 4.7).

Passive torques resulting from passive structures and the weight of the limb and dynamometer attachments were determined from three controlled passive motion trials throughout the participants joint range of motion. A warmup of three concentric-eccentric contractions at 50°·s^{-1} followed by 60 s of rest was then completed before a submaximal practice trial at three isometric joint angles (40°, 60°, 80°). Participants performed maximal isometric knee flexions and knee extensions at five randomised joint angles (20°, 40°, 60°, 80° and 90/100° depending on their available joint range of motion, where 0° = full knee extension) during which the knee joint angle was measured manually using a goniometer aligned with the lateral femoral epicondyle. Each contraction lasted 5 s and was performed once at each joint angle, followed by 60 s of rest. Encouragement and visual feedback were provided throughout the trial and two-minutes of rest was permitted during changes between limbs (dominant to non-dominant) and joint actions (knee flexion to knee extension).

Torque data were extracted unfiltered for processing for consistency across tests and goniometer angles were used to correct crank angles. The resulting data consisted of maximum voluntary isometric knee flexor and knee extensor joint torque for five joint angles on the dominant and non-dominant limb. These data were used to describe the relationship between torque production and joint angle in a monoarticular representation of the knee joint using a simple quadratic function (see Section 4.7.4, Equation 3). The maximum measured torque across the tested joint angles for each limb and joint action were identified as measured peak torque (PT_m).

Subject-specific parameters for peak isometric torques (T_0) optimal angle for torque production (θ_{opt}) and width of the torque-angle profile (k_2) were determined using simulated annealing (Corana et al., 1987) to minimise a cost function. The cost function was defined as the weighted root mean square (RMS) difference between the 'fitted' torque-angle profile and 'raw' torque-angle data (see Section 4.7.4, Equation 4). Initial parameter estimates were obtained from the literature (King et al., 2012) and given upper and lower bounds based on physiologically realistic values (**Table 6.1**). The calculated subject-specific parameters (**Table 6.1**) resulted in torque generator representations with a weighted RMS difference between measured and calculated torques of 2.4-2.5 Nm (1.6-2.1% of PT_m) for knee flexion and 2.5-3.5 Nm (1.2-2.1% of PT_m) for knee extension (**Table 6.2**). The function provided torque profiles with mean peak torque errors between optimised and measured torque of 8-10 Nm (5-7% of PT_m) for the knee flexors and 4-8 Nm (2-4% of PT_m).

6.3.3.3 Statistical Analyses

The two trials with best performance for all functional strength tests were identified and exported to SPSS (version 29.0 for Windows, Armonk, NY: IBM Corp) for analysis. All data were assessed for normality using the Shapiro-Wilk test. Heteroscedasticity was examined using scatterplots of the mean against mean difference and correlation between test-retest differences (absolute values). Differences between the two trials demonstrated non-normality and heteroscedasticity for some variables and so, within-session reliability analyses were performed on log transformed (base e, 'ln') data. Mean trials for functional tests, IKD data and asymmetry scores were all identified as normal and so all other analyses were performed on the raw data. Within-session reliability of the functional tests was assessed for the two best trials using the coefficient of variation (CV) and an intraclass correlation (ICC) for absolute agreement with 95% confidence intervals (CI; see Section 4.8.2). The Bland-Altman limits of agreement method and a paired samples t-test with statistical significance set at $p < 0.05$, were also conducted to assess systematic bias between trials. The magnitude of between-trial differences was calculated, using a corrected effect size (Hedges, g) as per recommendations for small samples (Lakens, 2013), with 95% confidence intervals (see Section 4.8.4).

Inter-limb asymmetries were quantified to detect both asymmetry magnitude and direction between the dominant and non-dominant limb (see Section 4.8.3, Equation 5). Kappa coefficients were calculated to determine the levels of agreement in the direction of asymmetry (i.e., how consistently the dominant or non-dominant limb was favoured) between isokinetic dynamometry and functional tests.

Table 6.1 Knee flexion and knee extension model parameters (mean ± SD) on the dominant (D) and non-dominant (ND) limb across the sample (*N* = 15)

		Knee Flexion			Knee Extension		
Parameter	**Description**	**D**	**ND**	**Bounds (LB; UB)**	**D**	**ND**	**Bounds (LB; UB)**
PT_m (Nm)	Measured peak isometric torque	149.09 ± 31.15	134.07 ± 35.77	n/a	209.35 ± 53.32	206.46 ± 38.93	n/a
T_0 (Nm)	Optimised peak isometric torque	155.87 ± 32.72	142.52 ± 38.32	±10% peak measured isometric torque	214.57 ± 55.11	206.04 ± 40.13	±10% peak measured isometric torque
θ_{opt} (°)	Optimal angle for T_0	134.75 ± 6.43	135.3 ± 4.19	131.78; 206.26	243.42 ± 8.39	244.77 ± 12.75	177.62; 315.13
k_2	Width of torque-angle profile	0.37 ± 0.17	0.37 ± 0.13	2.0; 0.2	0.75 ± 0.27	0.6 ± 0.42	2.0; 0.2
hR (°)	Distance from θ_{opt} to quadratic root of torque-angle profile	101.07 ± 21.51	98.94 ± 18.36	n/a	69.78 ± 15.45	86.66 ± 27.62	n/a

*Bounds taken from King et al., (2012), LB = lower bound, UB = upper bound. Joint angle representation is posterior for the knee flexors and anterior for the knee extensors

Table 6.2 Knee flexion and knee extension model performance outputs on the dominant (D) and non-dominant (ND) limb across the sample ($N = 15$)

		Knee Flexion		Knee Extension	
Parameter	**Description**	**D**	**ND**	**D**	**ND**
wRMS (%) [mean ± SD]	Weighted RMS difference between measured and fitted torques (% of PT_m)	1.63 ± 0.94	2.08 ± 1.97	1.16 ± 0.51	1.72 ± 1.25
Peak torque error (%) [RMS; Min-Max]	Difference between measured and T_0 (% of PT_m)	5.44 (-1.1; 8.62)	7.02 (-0.49; 9.94)	3.99 (-2.18; 8.45)	2.08 (-5.93; 3.34)

PT_m = measured peak isometric torque, T_0 = optimised peak isometric torque

Pearson's product-moment correlation coefficient (r) and the coefficient of determination (r^2) were used to assess the relationships between knee flexor/extensor strength and asymmetry from the IKD, with functional strength and asymmetry of the field tests. Statistical significance was set at $p < 0.05$. Pearsons r were interpreted as < 0.10 = no association, 0.10-0.39 = weak, 0.40-0.69 = moderate, 0.70-0.99 = strong, 1.00 = perfect (Kozinc & Šarabon, 2020). A paired samples t-test was conducted to determine systematic bias between the dominant and non-dominant limb, with accompanying effect sizes (g) calculated as detailed above.

6.4 Results

6.4.1 Reliability of Functional Strength Tests

Isometric Midthigh Pull

The IMTP demonstrated excellent within-session reliability for peak force and relative peak force, exhibiting acceptable CVs (< 10%) and ICC values of 0.92-0.98 (**Table 6.3**). Systematic bias varied from 0.98-1.02, indicating bidirectionality in IMTP outcome changes in the second trial (by ± 2%). In raw units, this corresponds to a systematic bias of -16 N and 26.1 N in peak force and -0.2 $N \cdot kg^{-1}$ and 0.2 $N \cdot kg^{-1}$ in relative peak force, for the dominant and non-dominant limb respectively. Limits of agreement for peak force and relative peak force on the dominant limb were equivalent to 319.2 N (27%) and 3.8 $N \cdot kg^{-1}$ (27%), respectively, compared to 183.3 N (15%) and 2.4 $N \cdot kg^{-1}$ (14%) on the non-dominant limb. Paired samples t-tests revealed no significant differences between trials and effect sizes were trivial.

Countermovement Jump

The CMJ demonstrated good to excellent within-session reliability for jump height and peak force, exhibiting acceptable CVs (< 10%) and ICC values of 0.86-0.93 (**Table 6.3**). Systematic bias varied from 0.94-0.98, indicating decreased CMJ outcomes in the second trial (by 2-6%). In raw units, this corresponds to a systematic bias of -1.1 cm and -1.0 cm in jump height and -22.1 N and -20.5 N in peak force, for the dominant and non-dominant limb respectively. Limits of agreement for jump height and peak force on the dominant limb were equivalent to 2.6 cm (17%) and 161.8 N (23%), respectively, compared to 2.4 cm (15%) and 129.4 N (17%) on the non-dominant limb. Paired samples t-tests revealed significant differences in jump height between trials for the dominant (p = 0.013) and non-dominant limb (p = 0 .005) and small effect sizes. No significant differences were observed in peak force between trials and effect sizes were trivial.

Horizontal Jump for Distance

The HJ demonstrated excellent within-session reliability for jump distance and peak force, exhibiting acceptable CVs (< 10%) and ICC values of 0.94-0.99 (**Table 6.3**). Systematic bias varied from 0.99-1.02, indicating bidirectionality in HJ outcome changes in the second trial (by 1 or 2%). In raw units, this corresponds to a systematic bias of -1.8 cm and -1.0 cm in jump distance and 9.2 N and 21.6 N in peak force, for the dominant and non-dominant limb respectively. Limits of agreement for jump distance and peak force on the dominant limb were equivalent to 9.1 cm (5%) and 135 N (16%), respectively, compared to 8.3 cm (5%) and 106.1 N (12%) on the non-dominant limb. Paired samples t-tests revealed no significant differences between trials and effect sizes were trivial.

Table 6.3 Within-session absolute and relative reliability measures of unilateral functional strength tests

		Isometric Midthigh Pull		Countermovement Jump		Horizontal Jump	
		PF (N)	**Rel PF (N.kg^{-1})**	**Jump Height (cm)**	**Peak Force (N)**	**Jump Distance (cm)**	**Peak Force (N)**
Trial 1 (X ± SD) [raw]	D	1371 ± 357	17 ± 4	16 ± 2	777 ± 128	174 ± 18	864 ± 137
	ND	1429 ± 400	18 ± 4	17 ± 3	792 ± 144	176 ± 17	884 ± 121
Trial 2 (X ± SD) [raw]	D	1355 ± 364	17 ± 4	15 ± 2	757 ± 118	172 ± 16	886 ± 155
	ND	1455 ± 377	18 ± 4	16 ± 2	770 ± 129	175 ± 16	893 ± 118
Trial 1 (X ± SD) [ln]	D	7.19 ± 0.25	2.82 ± 0.22	2.79 ± 0.14	6.64 ± 0.17	5.15 ± 0.11	6.75 ± 0.15
	ND	7.23 ± 0.27	2.85 ± 0.21	2.83 ± 0.18	6.66 ± 0.18	5.17 ± 0.10	6.78 ± 0.14
Trial 2 (X ± SD) [ln]	D	7.18 ± 0.27	2.80 ± 0.23	2.73 ± 0.13	6.62 ± 0.15	5.15 ± 0.10	6.77 ± 0.17
	ND	7.25 ± 0.25	2.87 ± 0.22	2.77 ± 0.14	6.63 ± 0.16	5.16 ± 0.09	6.79 ± 0.13
Systematic Bias [antilog]	D	0.98	0.99	0.94	0.98	0.99	1.02
	ND	1.02	1.01	0.94	0.97	0.99	1.01
LoA [antilog]	D	1.27	1.27	1.17	1.23	1.05	1.16
	ND	1.15	1.14	1.15	1.17	1.05	1.12
Lower LoA [antilog]	D	0.78	0.78	0.80	0.80	0.94	0.88
	ND	0.89	0.89	0.82	0.83	0.95	0.90
Upper LoA [antilog]	D	1.25	1.25	1.10	1.20	1.04	1.18
	ND	1.18	1.15	1.08	1.14	1.04	1.13
CV % [raw]	D	5.79	5.76	5.48	5.32	1.62	3.48
	ND	3.95	3.76	5.34	4.55	1.41	3.12
ICC (95% CI) [ln]	D	0.95 (0.86-0.98)	0.92 (0.77-0.97)	0.86 (0.45-0.96)	0.89 (0.68-0.96)	0.98 (0.94-0.99)	0.94 (0.84-0.98)
	ND	0.98 (0.94-0.99)	0.98 (0.93-0.99)	0.91 (0.51-0.98)	0.93 (0.81-0.98)	0.99 (0.96-1.00)	0.95 (0.86-0.98)
t-test [ln]	D	$p = 0.630$	$p = 0.692$	$p = 0.013$*	$p = 0.337$	$p = 0.250$	$p = 0.272$
	ND	$p = 0.222$	$p = 0.552$	$p = 0.005$*	$p = 0.239$	$p = 0.315$	$p = 0.445$
Effect size (95% CI) [raw]	D	-0.04 (-0.27 to 0.18)	-0.05 (-0.32 to 0.22)	-0.42 (-0.79 to -0.10)	-0.16 (-0.51 to 0.18)	-0.10 (-0.24 to 0.03)	0.14 (-0.09 to 0.38)
	ND	0.06 (-0.05 to 0.19)	0.06 (-0.09 to 0.22)	-0.40 (-0.68 to -0.18)	-0.15 (-0.41 to 0.08)	-0.06 (-0.18 to 0.07)	0.07 (-0.15 to 0.31)

D = dominant limb, ND = non-dominant limb, X ± SD = mean ± standard deviation, ln = log-transformed data, LoA = limit of agreement, CV = coefficient of variation, ICC = intraclass correlation, CI = confidence interval, PF = peak force, Rel PF = relative PF, * = statistically significant difference between trial 1 and trial 2 ($p < 0.05$)

6.4.2 Relationships Between Maximum Knee Flexor/Extensor Isometric Strength and Functional Strength

Correlations between knee flexor/extensor strength and functional performance metrics are reported in **Table 6.4**. Significant positive correlations were identified between knee flexion T_0 and IMTP peak force on both limbs (*r* = 0.53-0.54; *p* = 0.040-0.042, r^2 = 0.28-0.29). Significant positive correlations were also identified between knee extension PT_m and HJ distance (*r* = 0.53; *p* = 0.044; r^2 = 0.28), and knee extension T_0 and HJ distance (*r* = 0.54; *p* = 0.036; r^2 = 0.30). No other significant correlations were observed between knee flexor/extensor strength and functional strength metrics.

6.4.3 Relationships Between Asymmetries in Maximum Knee Flexor/Extensor Isometric Strength and Asymmetries in Functional Strength

When assessing inter-limb differences in knee flexor/extensor strength using isokinetic dynamometry, paired samples t-tests revealed significant differences in knee flexion PT_m (*p* = 0.044; *g* = -0.42; **Table 6.5**). No other significant differences were observed between limbs for isokinetic dynamometry and effect sizes were trivial to small. When assessing inter-limb differences using functional strength tests, significant differences were identified in IMTP peak force (*p* = 0.024; *g* = -0.20) and relative peak force (*p* = 0.045; *g* = -0.22; **Table 6.5**). No other significant differences were observed between limbs for field-based testing methods and effect sizes were trivial to small. All but two correlations indicate negative relationships between knee flexor/extensor asymmetry and asymmetry in the field tests; however, none of the correlations were statistically significant (**Table 6.6**). In all but one comparison, kappa coefficients revealed poor to slight consistency (-0.36 to 0.15) in asymmetry between isokinetic dynamometry and functional tests, but moderate consistency (0.45) between knee extension ASI and HJ distance ASI (**Table 6.7**).

Table 6.4 Pearsons r correlations between knee flexor/extensor maximum isometric strength on the isokinetic dynamometer and functional strength

			Isometric Midthigh Pull				**Countermovement Jump**				**Horizontal Jump**			
			D		**ND**		**D**		**ND**		**D**		**ND**	
			PF	**Rel PF**	**PF**	**Rel PF**	**JH**	**PF**	**JH**	**PF**	**Distance**	**PF**	**Distance**	**PF**
Knee Flexion	**D**	PT_m	0.49	0.31	0.48	0.30	-0.12	0.50	-0.31	0.40	0.17	0.35	-0.18	0.31
		T_0	0.54*	0.37	0.53*	0.37	-0.10	0.48	-0.29	0.36	0.26	0.37	-0.08	0.33
	ND	PT_m	0.15	-0.10	0.11	-0.15	-0.21	0.44	-0.51	0.24	0.16	0.27	-0.13	0.20
		T_0	0.17	-0.09	0.14	-0.13	-0.19	0.44	-0.49	0.25	0.17	0.27	-0.14	0.20
Knee Extension	**D**	PT_m	0.36	0.08	0.34	0.09	-0.21	0.13	-0.33	0.02	0.32	-0.14	0.00	0.04
		T_0	0.35	0.09	0.34	0.11	-0.17	0.11	-0.30	-0.02	0.36	-0.16	0.06	-0.01
	ND	PT_m	0.44	0.32	0.35	0.22	0.14	0.05	-0.22	-0.13	0.53*	-0.23	0.23	-0.24
		T_0	0.44	0.35	0.36	0.25	0.19	0.04	-0.16	-0.14	0.54*	-0.23	0.28	-0.24

D = dominant limb, ND = non-dominant limb, PF = peak force (N), Rel PF = relative peak force ($N.kg^{-1}$), JH = jump height (cm), PT_m= measured peak isometric torque (Nm), T_0 = optimised peak isometric torque (Nm), * = statistically significant correlation ($p < 0.05$)

Table 6.5 Mean (± SD) functional strength data and statistics for comparisons between the dominant and non-dominant limb

	Knee Flexion		**Knee Extension**		**Isometric Midthigh Pull**		**Countermovement Jump**		**Horizontal Jump**	
	PT_m	T_0	PT_m	T_0	**PF**	**Rel PF**	**JH**	**PF**	**Distance**	**PF**
Dominant (X ± SD) [raw]	149 ± 31	156 ± 33	209 ± 53	215 ± 55	1363 ± 351	17 ± 4	16 ± 2	767 ± 116	173 ± 17	875 ± 142
Non-dominant (X ± SD) [raw]	134 ± 36	143 ± 38	206 ± 39	206 ± 40	1442 ± 386	18 ± 4	17 ± 2	781 ± 133	176 ± 17	888 ± 116
Asymmetry % [Abs, raw]	15.8 ± 9.7	15.7 ± 10	12.0 ± 9.3	12.5 ± 9.22	8.9 ± 4.8	8.4 ± 5.0	8.9 ± 6.8	6.4 ± 4.5	4.5 ± 3.0	5.7 ± 4.2
t-test [raw]	$p = 0.044$*	$p = 0.102$	$p = 0.740$	$p = 0.348$	$p = 0.024$*	$p = 0.045$*	$p = 0.128$	$p = 0.408$	$p = 0.340$	$p = 0.438$
Effect size (95% CI) [raw]	-0.42 (-0.87 to -0.02)	-0.35 (-0.81 to 0.06)	-0.06 (-0.39-0.27)	-0.17 (-0.51 to 0.16)	-0.20 (-0.40 to -0.04)	-0.22 -0.46 to -0.01)	-0.33 (-0.77 to 0.08)	-0.11 (-0.38 to 0.15)	-0.14 (-0.38 to 0.09)	-0.10 (-0.34 to 0.13)

PT_m= measured peak isometric torque (Nm), T_0 = optimised peak isometric torque (Nm), PF = peak force (N), Rel PF = relative peak force ($N.kg^{-1}$), JH = jump height (cm), * = statistically significant difference between limbs ($p < 0.05$)

Table 6.6 Pearsons r correlations between asymmetry in knee flexor/extensor maximum isometric strength and asymmetry in functional strength

		Isometric Midthigh Pull ASI		Countermovement Jump ASI		Horizontal Jump ASI	
		PF	Rel PF	JH	PF	Distance	PF
Knee Flexion ASI	PT_m	-0.12	-0.15	-0.25	-0.30	-0.03	-0.16
	T_0	-0.12	-0.14	-0.24	-0.21	-0.09	-0.12
Knee Extension ASI	PT_m	-0.20	-0.31	-0.12	-0.16	0.31	-0.51
	T_0	-0.21	-0.32	-0.09	-0.07	0.32	-0.47

ASI = asymmetry index score (%), PT_m= measured peak isometric torque (Nm), T_0 = optimised peak isometric torque (Nm), PF = peak force (N), Rel PF = relative peak force ($N.kg^{-1}$), JH = jump height (cm), * = statistically significant correlation ($p < 0.05$)

Table 6.7 Kappa coefficients and descriptive levels of agreement for the changes in asymmetry direction between isokinetic dynamometry and functional strength tests

		Isometric Midthigh Pull ASI		Countermovement Jump ASI		Horizontal Jump ASI	
		PF	Rel PF	JH	PF	Distance	PF
Knee Flexion ASI	PT_m / T_0	-0.25 (poor)	-0.20 (poor)	0.08 (slight)	0.15 (slight)	0.04 (slight)	-0.24 (poor)
Knee Extension ASI	PT_m / T_0	0.00 (poor)	0.08 (slight)	-0.08 (poor)	0.00 (poor)	0.45 (moderate)	-0.36 (poor)

ASI = asymmetry index score (%), PT_m= measured peak isometric torque (Nm), T_0 = optimised peak isometric torque (Nm), PF = peak force (N), Rel PF = relative peak force ($N.kg^{-1}$), JH = jump height (cm)

6.4.4 Relationships Between Inter-Limb Asymmetries and Performance

For asymmetry determined by isokinetic dynamometry (**Table 6.8**), significant positive correlations were identified between knee extension PT_m asymmetry and knee extension PT_m (r = 0.72; p = 0.003; r^2 = 0.52) and T_0 (r = 0.68; p = 0.005; r^2 = 0.47). Significant positive correlations were also identified between knee extension T_0 asymmetry and knee extension T_0 (r = 0.71; p = 0.003; r^2 = 0.50) and PT_m (r = 0.73; p = 0.002; r^2 = 0.53). Significant positive correlations were identified between knee flexion PT_m/T_0 asymmetries and IMTP relative peak force (r = 0.55; p = 0.033-0.036; r^2 = 0.30-0.31).

For asymmetry determined by functional tests (**Table 6.8**), significant positive correlations were observed between HJ distance asymmetry and knee flexion PT_m/T_0 (r = 0.56-0.62; p = 0.014-0.028; r^2 = 0.32-0.38) and knee extension PT_m/T_0 (r = 0.52-0.60; p = 0.019-0.046; r^2 = 0.27-0.36) on both limbs. Significant positive correlations were also identified between HJ peak force asymmetry and peak force in the CMJ (r = 0.53; p = 0.044; r^2 = 0.28) and HJ (r = 0.56; p = 0.029; r^2 = 0.32). Significant positive correlations were shown between CMJ height and peak force asymmetries and HJ distance (r = 0.53-0.55; p = 0.035-0.042; r^2 =0.28- 0.30). A significant negative correlation was observed between CMJ height asymmetry and CMJ height (r = -0.57; p = 0.027; r^2 = 0.32).

6.5 Discussion

This study firstly sought to examine the within-session, test-retest reliability of functional tests for the assessment of muscular strength. Findings demonstrated acceptable absolute reliability for all tests and metrics (CVs < 10%) indicative of reduced individual variability between trials. Relative reliability was excellent for the IMTP and HJ, and good to excellent for the CMJ, which indicates ranked vertical jumping performance was relatively consistent between trials. Bland-Altman analyses revealed smaller systematic bias and narrower limits of agreement for the HJ compared to the other field-tests, particularly in jump distance. The second aim was to explore the associations in strength and inter-limb asymmetry between maximal and functional tests. Significant positive relationships were observed between isometric knee flexor/extensor strength, and some functional tests, but predictors accounted for ≤ 30% of the variance in the outcome. Between limb differences were identified by isokinetic dynamometry and the IMTP, with the dominant limb identified as the stronger limb in the former but weaker in the latter, yet no statistically significant relationships in asymmetry between methods were observed. Kappa coefficients also revealed asymmetry direction was largely inconsistent between isokinetic dynamometry and functional tests. Significant relationships were present between knee extensor strength asymmetry and knee extensor strength, and knee flexor strength asymmetry and IMTP performance. Functional testing also identified significant relationships between HJ asymmetry and knee extension strength and jumping performance, and CMJ asymmetry and jumping performance. Most relationships suggest larger asymmetries were associated with better isometric strength and functional performance, but the negative relationship between CMJ height asymmetry and CMJ height relates larger asymmetries with weaker performance.

Table 6.8 Pearsons r correlations between asymmetry in knee flexor/extensor isometric strength, isometric strength and functional strength

		Knee Flexion				**Knee Extension**				**Isometric Midthigh Pull**				**Countermovement Jump**				**Horizontal Jump**			
		D		**ND**		**D**		**ND**		**D**		**ND**		**D**		**ND**		**D**		**ND**	
		PT_m	T_0	PT_m	T_0	PT_m	T_0	PT_m	T_0	**JH**	**PF**	**PF**	**Rel PF**	**PF**	**Rel PF**	**JH**	**PF**	**Dist.**	**PF**	**Dist.**	**PF**
KF ASI	PT_m	0.27	0.28	-0.48	-0.49	0.07	0.03	-0.08	-0.06	0.39	0.49	0.42	0.55*	0.12	0.07	0.30	0.23	-0.05	0.12	-0.07	0.21
	T_0	0.30	0.33	-0.45	-0.47	0.06	0.05	-0.06	-0.03	0.38	0.50	0.41	0.55*	0.11	0.06	0.29	0.18	0.03	0.17	0.05	0.24
KE ASI	PT_m	0.45	0.43	0.35	0.36	.718*	.682*	0.15	0.12	0.07	-0.24	0.14	-0.10	-0.44	0.16	-0.29	0.20	-0.03	0.06	-0.20	0.36
	T_0	0.47	0.45	0.40	0.40	0.76*	0.71*	0.17	0.13	0.03	-0.27	0.11	-0.13	-0.44	0.14	-0.30	0.13	0.00	0.03	-0.17	0.31
IMTP ASI	**PF**	0.04	0.00	0.12	0.09	-0.15	-0.02	0.16	0.17	0.10	0.15	-0.21	-0.24	0.25	-0.21	-0.20	-0.15	-0.12	-0.23	0.00	-0.12
	RelPF	0.03	0.00	0.12	0.10	-0.21	-0.06	0.21	0.21	0.12	0.19	-0.19	-0.21	0.32	-0.20	-0.17	-0.17	-0.07	-0.20	0.01	-0.15
CMJ ASI	**JH**	0.31	0.30	0.45	0.45	0.05	0.17	0.41	0.39	0.20	0.27	0.05	0.05	0.22	-0.24	-0.57*	-0.43	0.55*	-0.27	0.39	-0.29
	PF	0.12	0.16	0.29	0.27	0.11	0.19	0.34	0.32	-0.22	-0.17	-0.19	-0.17	0.04	0.12	-0.27	-0.39	0.53*	-0.10	0.35	-0.26
HJ ASI	**Dist.**	0.62*	0.59*	0.56*	0.60*	0.59*	0.57*	0.57*	0.52*	0.37	0.14	0.41	0.18	-0.25	0.44	-0.46	0.22	0.33	0.13	-0.24	0.05
	PF	0.33	0.36	0.40	0.37	-0.28	-0.23	0.01	0.02	0.20	0.26	0.24	0.27	0.12	0.53*	0.01	0.30	0.18	0.56*	0.05	0.13

D = dominant limb, ND = non-dominant limb, ASI = asymmetry index score (%), KF = knee flexion, KE = knee extension, IMTP = isometric midthigh pull, CMJ = countermovement jump, HJ = horizontal jump, PT_m= measured peak isometric torque (Nm), T_0 = optimised peak isometric torque (Nm), PF = peak force (N), Rel PF = relative peak force (N/kg), JH = jump height (cm), Dist. = distance, * = statistically significant correlation ($p < 0.05$)

All field tests exhibited acceptable absolute and relative reliability, as evidenced by CVs below 10%, and good to excellent ICCs across limbs and metrics (**Table 6.3**). High within-session reliability has been reported previously in functional strength and performance tasks (Bishop et al., 2019a, 2021b; Haff et al., 2015; McCubbine et al., 2018; Thomas et al., 2017) indicating limited variability in individual and ranked performance across repeated measures. Bishop et al., (2021b) reported small individual variability (CV = 2.82-4.18%) and good to excellent relative reliability (ICC = 0.81-0.99) in vertical and horizontal jump height and distance. High reliability has also been demonstrated in multijoint isometric tasks; however, some evidence suggests metric sensitivity in time-dependent variables (Brady et al., 2018; Dos'Santos et al., 2017c; Guppy et al., 2019). Guppy et al., (2019) investigated the effect of hip, knee, and barbell position on IMTP kinetics and deemed most force-time characteristics as acceptable (CV < 15%; ICC > 0.7). However, unacceptable reliability was observed for time to peak force (CV = 24.2-73.5%; ICC = 0.25-0.88), rate force development at time-specific intervals (CV = 19.8-51.4%; ICC = 0.47-0.88), and peak impulse (CV = 28.3-80.7%; ICC = 0.51-0.91) in all testing positions. Despite this, IMTP impulse and rate of force development characteristics have been shown elsewhere to meet absolute and relative reliability criteria (Beckham et al., 2012; Comfort et al., 2014; Dos'Santos et al., 2019; Thomas et al., 2015). A potential reason for such disparities could be variability in task familiarity, as the athletes recruited by Guppy et al., (2019) were often performing the IMTP for the first-time during familiarisation, yet others were performing the IMTP regularly for monitoring purposes (Haff et al., 2015). The current sample were similarly unfamiliar with the IMTP, thus overall high reliability may be attributed to metric selection.

The HJ demonstrated the highest reliability of all functional tests, with jump distance exhibiting the smallest CV (1.41-1.62%) and highest ICC (0.98-0.99) compared to all other metrics (**Table 6.3**). Conversely, the CMJ exhibited larger individual variability (CV = 4.55-5.48%) as well as the lowest relative reliability (ICC = 0.86-0.93) and notably larger 95% ICC confidence intervals for jump height (D: 0.45-0.96; ND: 0.51-0.98) and peak force (D: 0.68-0.96; ND: 0.81-0.98). Bland-Altman analyses also revealed smaller systematic bias and narrower limits of agreement for HJ distance (-1% and 5%, respectively) and peak force (1-2% and 12-16%, respectively) compared to IMTP peak force (±2% and 15-27%, respectively) and relative peak force (±1% and 14-27%, respectively), and CMJ jump height (-6% and 15-17%, respectively) and peak force (-2-

3% and 17-23%, respectively). This is in contrast to the findings of Bishop et al., (2021b) whereby greater variability was observed in horizontal hopping than for the unilateral CMJ. Better reliability in the HJ found here may be partly explained by the methodological approach, as participants were free to land on two limbs to encourage maximal effort, and trials that improved by more than 10 cm were repeated to reduce the effect of familiarisation. Resultantly, the maximum variability in any participants HJ performance was restricted whereas, fluctuations in performance of the IMTP and CMJ were unregulated. Nonetheless, reduced variability in horizontal versus vertical jumping has been documented previously amongst both male and female recreational athletes in investigations that did not adopt this approach (Maulder & Cronin, 2005; Meylan et al., 2009). Jump height also exhibited significant differences between trials, with trivial to moderate effect sizes for the dominant and non-dominant limb (**Table 6.3**), despite only small changes in the mean from trial 1 (D: 16 ± 2 cm; ND: 17 ± 3 cm) to trial 2 (D: 15 ± 2 cm; ND: 16 ± 2 cm). Significant differences may be partly attributed to the measurement scale for jump height, which is much smaller than for the other investigated metrics. Nonetheless, given the collective evidence from the current study and presented literature, it may be concluded that CMJ jump height is not sufficiently reliable, particularly when required to detect small changes in performance between trials or limbs. Jump kinetics are likely to provide better insight into 'real' differences, but in the absence of the appropriate equipment, practitioners may benefit from prioritising horizontal jumping in performance assessments.

Significant positive relationships were found between isometric knee flexor/extensor strength and two of the investigated functional strength tests (**Table 6.4**). Firstly, moderate correlations were observed between dominant knee flexion T_0 and IMTP peak force on both limbs. Such relationships may be expected considering similarities in force development during isometric tasks; however, it is surprising to observe a relationship with the knee flexors given the IMTP relies predominantly on the hip and knee extensors (Kuki et al., 2018; McMahon et al., 2015). Accordingly, the coefficient of determination is low, indicating knee flexion T_0 accounted for just 28-29% of the variance in IMTP peak force. Furthermore, the IMTP was conducted according to recommendations which specify knee and hip angles of 125-145° and 140-150°, respectively should be adopted for maximal force production (Beckham et al., 2012, 2012; Dos'Santos et al., 2017d). Knee extensor peak torque may, however, be suboptimal due to the shorter length of the biarticular rectus femoris in a more flexed hip position when seated. Thus, stronger relationships may have been observed for knee extension strength measured in a more extended hip angle. Furthermore, joint angles are subject to change during task performance (Arampatzis et al., 2004, 2005; Beckham et al., 2018), which limits comparison between tests. Moderate correlations were identified in non-dominant knee extension strength (PT_m and T_0) and HJ distance on the dominant limb (**Table 6.4**). However, the coefficient of determination indicates only 28-30% of the variance in HJ distance can be explained by isometric knee extensor strength, leaving ≥ 70 % of the variance unexplained by the model. This can likely be attributed to differences in task performance, as maximum isometric strength is assessed under controlled, static loading conditions whereas jumping reflects the ability to produce force under time constraints and so, is highly influenced by force- and power-velocity characteristics (Yamauchi & Ishii, 2007). Isokinetic dynamometry also offers optimal conditions for force production (muscle length and velocity) at a single isolated joint whereas jumping is highly dependent on technique and involves contributions from the ankle and hip, particularly during the propulsion phase of horizontal hopping (Kotsifaki et al., 2021). Thus, the relationship between maximum knee strength and functional dynamic tasks is questionable.

When assessing inter-limb differences using the gold-standard method, significant differences were observed between the dominant and non-dominant limb in knee flexion PT_m and effect sizes were trivial to moderate (**Table 6.5**). Results indicated enhanced knee flexor strength on the dominant limb, with it outperforming the non-dominant limb by 15 Nm in knee flexion PT_m. Conflicting evidence has been reported with regards to the effect of limb dominance, with some studies observing inter-limb differences in strength and functional performance (Dos'Santos et al., 2017b; Jones & Bampouras, 2010; Newton et al., 2006; Rouissi et al., 2016; Ruas et al., 2015; Steidl-Müller et al., 2018), whilst others reported none (Greenberger & Paterno, 1995; McCurdy & Langford, 2005; McGrath et al., 2016; Östenberg et al., 1998; Vaisman et al., 2017). Limb distinction according to dominance has been recommended over a right/left limb comparison to avoid diluting inter-limb differences (Dos'Santos et al., 2017b, 2018c; Jones & Bampouras, 2010; Newton et al., 2006). However, limb dominance determined subjectively by the participant, as done for this study, may not be suitable and larger differences may have been observed if the limb definition was based on task performance instead (Ceroni et al., 2012; Kuki et al., 2019). Thirteen of the athletes (87%) identified their right limb as the dominant limb when asked which limb they would usually kick a ball with yet, two participants demonstrated higher PT_m on the left limb which could undermine the significance of inter-limb differences. No other significant differences were identified in isometric knee strength; however, incongruence between dominance and performance may explain the lack of relationships for the knee extensors as five athletes (33%) demonstrated higher PT_m on the non-dominant limb. The IMTP was the only functional task to identify inter-limb differences, with the non-dominant limb outperforming the dominant limb by 79 Nm in peak force and 1 $N.kg^{-1}$ in relative peak force (**Table 6.5**). Better performance outcomes were also observed on the non-dominant limb, exhibiting trivial to moderate effect sizes despite no significant differences between limbs. This could reflect sport-specific adaptations in the current sample of hockey players, as the rules stipulate athletes must carry a right-handed hockey stick regardless of limb preference. Resultantly, players often adopt a semi-crouched position with the left leg acting as the lead leg for stance and when striking the ball (López De Subijana et al., 2010). Hockey can, therefore, be considered an 'asymmetrical' sport (Bussey, 2010; Kalata et al., 2020) with functional adaptations likely to occur on the left limb due to its role in maintaining stability and generating force during play (Krzykała, 2010). This is in opposition to limb differences measured by isokinetic dynamometry which identified the dominant limb as the stronger of the two limbs, indicating functional adaptations do not necessarily reflect strength adaptations.

The isokinetic dynamometer identified larger inter-limb asymmetries than field-based testing, with asymmetries up to 16% and 13% for the knee flexors and knee extensors, respectively compared to 5-9% in the functional tests (**Table 6.5**). Previous research in recreational male athletes has reported similar interlimb asymmetries in knee flexion and extension strength of 19% and 15%, respectively (Barrué-Belou et al., 2024). Jumping asymmetries of 5-10% in male and female team-sport athletes at preseason and smaller asymmetries in horizontal jumping have also been shown (Fort-Vanmeerhaeghe et al., 2021) and unilateral IMTP asymmetries of approximately 10% have been identified in male collegiate athletes (Kuki et al., 2019). Elite athletes from more varied sports may exhibit smaller IMTP asymmetries (< 3%; (Dos'Santos et al., 2017c) thus, small IMTP asymmetries (1-4%) in the current study may reflect skill-level and training amongst the sample. Despite the presence of inter-limb differences, there were no significant correlations between asymmetries determined by isokinetic dynamometry and those determined by functional tests (**Table 6.6**). It is of note, however, that all but two of the relationships between isometric and functional strength metrics were negative, indicating functional asymmetries decreased as knee flexor/extensor asymmetries increased. Weak to moderate correlations have been documented previously between isometric knee extensor strength asymmetry and hopping (Kozinc & Šarabon, 2020) and others have reported isokinetic strength and CMJ tests to be widely independent methods of assessment for inter-limb asymmetry (Menzel et al., 2013). This likely reflects the different strength components being assessed by each test, particularly when comparing isometric tasks to those which utilise the stretch-shortening cycle (Bailey et al., 2013; Furlong & Harrison, 2014). Additionally, it is now well-established that asymmetry is highly task-specific (Bishop et al., 2019c, 2021a; Dos'Santos et al., 2017b; Read et al., 2021) such that fluctuations in magnitude and direction across tests should be expected. The current findings demonstrate poor to slight consistency in asymmetry direction across most comparisons, and moderate consistency between knee extension strength and HJ distance (**Table 6.7**). Thus, tests may not be used interchangeably for the assessment of asymmetry, particularly when task demands are vastly different. It has, however, been suggested that stronger individuals may demonstrate some carry-over of asymmetry between tasks that is not observed in weaker individuals due to increased variability (Bailey et al., 2013, 2015).

The largest associations between asymmetry and performance were measured by isokinetic dynamometry (**Table 6.8**), with moderate to strong positive correlations observed between knee extensor asymmetry (PT_m and T_0) and knee extension strength on the dominant limb (PT_m and T_0). Stronger relationships can be expected within the same task compared to between tasks as evidenced elsewhere for isokinetic knee extensor strength and vertical jumping (Menzel et al., 2013). However, this relationship suggests stronger individuals exhibit larger strength asymmetries which contradicts previous findings in recreational and competitive athletes (Bailey et al., 2013, 2015; Bazyler et al., 2014). Additional moderate positive correlations were identified between HJ distance asymmetry and knee flexor and knee extensor strength (PT_m and T_0) which ascertains the notion greater isometric knee strength is associated with larger asymmetries in both isometric strength and functional performance (**Table 6.8**). Training interventions have been recommended to reduce inter-limb asymmetries due to their associations with increased injury risk (Brumitt et al., 2020; Croisier et al., 2008; Fort-Vanmeerhaeghe et al., 2022; Fousekis et al., 2011; MacSweeney et al., 2023; Read et al., 2018; Steidl-Müller et al., 2018) and weaker performance outcomes (Bishop et al., 2019a, 2019b, 2021b; Fort-Vanmeerhaeghe et al., 2020; Madruga-Parera et al., 2020, 2021). However, this finding indicates strength and asymmetry may go hand-in-hand and inter-limb differences may, in some cases, reflect optimal function if the goal is maximal isometric force production. Thus, decision-making should be appropriately tailored to the performance demands within the sporting context. Positive relationships were found within and between force and outcome (height and distance) metrics, with CMJ peak force asymmetry positively associated with horizontal jump distance on the dominant limb (**Table 6.8**). The association with underlying kinetics suggests jumping performance indicated by height or distance, may be used as a cost-effective alternative to testing with force plates. The only significant negative relationship between asymmetry and performance was observed between CMJ height asymmetry and CMJ height on the non-dominant limb. This aligns with the results of numerous investigations which have found associations between larger jumping asymmetries and weaker performance in jumping, sprinting and change-of direction speed performance (Bishop et al., 2019d, 2019b, 2021b; Maloney et al., 2017); however, asymmetries may not track over time (Bishop et al., 2022c) and absent relationships are also reported (Dos'Santos et al., 2017b; Lake et al., 2011; Lockie et al., 2014). Thus, conflicting findings in both the present study and wider literature indicates a battery of tests is necessary for a comprehensive assessment of inter-limb asymmetry to be made.

This study provides useful information about isometric strength and functional performance and asymmetries in university-level hockey athletes amongst whom there is a paucity in the literature. One limitation of this study, however, was the sole use of isometric testing to assess knee flexor/extensor strength despite obvious differences between isometric and dynamic strength capacities. Isometric testing was conducted to reduce limitations associated with lack of familiarisation (Nugent et al., 2015) as errors were expected to be lower due to reduced task complexity compared with isokinetic testing. The influence of submaximal torque measurements on torque representations can also be reduced through curve-fitting techniques as employed in this study. However, this process required a tailored approach that could not be applied to new datasets without further investigation. The measurement approach would also be improved by making multiple measurements at each joint angle to enable assessment of reliability as done for the functional strength tests. Additionally, maximum strength asymmetries could not be interpreted using sample-specific thresholds as recommended in the literature, which typically utilise subject-specific CVs and the smallest worthwhile change from the group (Bishop, 2021; Dos'Santos et al., 2021). This was, however, beyond the scope of the current investigation. Lastly, the current findings on asymmetry relate specifically to the studied sample and cannot be generalised more widely due to the highly variable nature of asymmetry. Thus, further research amongst larger and more diverse sporting cohorts, including both cyclic and acyclic sports, is warranted to explore the relationships between strength, performance and asymmetries.

6.6 Conclusion

In summary, field-based strength tests provide a reliable means to assess functional performance, with horizontal jumping offering the most robust method of assessment. Isometric knee strength was associated with IMTP kinetics and HJ distance despite different performance demands, particularly between isometric and dynamic tasks. Inter-limb asymmetries determined by different tasks were not related but, larger strength and jumping asymmetries were generally indicative of better maximal strength and functional performance. A battery of tests is necessary to provide a comprehensive assessment of athletic strength, performance and asymmetries and results should be interpreted according to the sporting demands to ensure appropriate decision-making.

Chapter 7: Jumping Performance and Inter-Limb Asymmetries: A Season-Long Study in University Team-Sport Athletes

7.1 Rationale

The previous chapter demonstrates functional strength tests may be used to assess components of strength and inter-limb asymmetry, providing reliable measures that reflect maximum strength. Performance-based metrics obtained during vertical and horizontal jumping (e.g., jump height and distance) are considered the simplest and most cost-effective means to measure functional performance, requiring only a jump mat or tape measure. Reliability analyses conducted in Chapter 6 reiterates variability between tasks and metrics reported in the literature (González-García et al., 2024; Merrigan et al., 2020; Pérez-Castilla et al., 2021) and so, test-retest reliability should always be established within the research context and for the sample under investigation. Jumping performance and inter-limb asymmetry are commonly assessed for the purpose of athlete monitoring (Bishop et al., 2020b, 2021c, 2022c; Fort-Vanmeerhaeghe et al., 2021; Williams et al., 2011), with fluctuations observed over the course of a season expected in relation to training and match load. Inconsistencies in asymmetry direction have also been observed in athletes over time, such that assessment of the magnitude alone would give a false impression of stability in asymmetry (Bishop et al., 2020b; Fort-Vanmeerhaeghe et al., 2021). Disparities between sexes and sports in jumping performance and asymmetry are expected due to physiological and training differences, with males expected to outperform females and training adaptations to reflect sport-specific demands (Bishop et al., 2019b; Dai et al., 2019; Kozinc et al., 2022; McMahon et al., 2017c). However, the association between changes in performance and asymmetry over time warrants further investigation from more frequent testing sessions and across diverse samples. Thus, the purpose of this investigation was to assess seasonal variation in jump performance and inter-limb asymmetry magnitude and direction between sexes and sports.

7.2 Introduction

Jumping, both horizontally and vertically, occurs frequently in multidirectional team sports, with varying demands between sports and positions (Delextrat et al., 2015; Fox et al., 2013; Taylor et al., 2017). In netball for example, Fox et al., (2013) observed roughly one jump per minute amongst the Australian female team, with notable positional differences for the goal shooter who performed 36.3 jumps fewer than the wing attack during the game. Optimal jump performance can be attributed to strength, power and technique, with improved outcomes observed amongst individuals who are able to apply a larger impulse before take-off (Chalitsios et al., 2019; McMahon et al., 2017; Rice et al., 2017). Consequently, jump tests, such as the countermovement jump (CMJ) and horizontal jump (HJ), are widely used to measure functional strength in athletes in both research and applied settings (Bishop et al., 2019a, 2021b; Cormie et al., 2010a; Lamas et al., 2012). Differences in jump performance, often measured as jump height or distance, have been observed between sexes, which reflect advantageous muscle architecture and a more efficient jump strategy amongst males (Alegre et al., 2009; Chalitsios et al., 2019; Eisenmann & Malina, 2003; McMahon et al., 2017). Additionally, 'sport-specific signatures' have been observed in relation to jump performance, such that outdoor athletes demonstrate force-dominant rather than time-dominant profiles, enabling them to jump higher than indoor athletes (Laffaye et al., 2014). Performance metrics from jump tests also offer a time- and cost-effective alternative to maximum and functional strength testing with force plates, which is useful in an applied setting where resources may be limited. Therefore, the utility of vertical and horizontal jump tests for longitudinal monitoring in athletes warrants further discussion.

Inter-limb asymmetry, referring to the difference in performance or function between limbs, may develop in response to high-intensity unilateral actions and has been associated with increased injury risk and weaker performance (Bishop et al., 2019a, 2019b, 2021b; Brumitt et al., 2020; Fort-Vanmeerhaeghe et al., 2020, 2022; MacSweeney et al., 2023; Madruga-Parera et al., 2020, 2021; Steidl-Müller et al., 2018). Assessment of inter-limb asymmetries during jump tests has become commonplace in clinical and sporting settings for a range of purposes, including training specialisation, injury mitigation and rehabilitation (Carvalho et al., 2016; Fort-Vanmeerhaeghe et al., 2022; Gonzalo-Skok et al., 2019; Jordan et al., 2015; Moreno-Azze et al., 2021). The calculation of asymmetry, however, has been widely debated over recent years due to methodological flaws and inconsistencies (Parkinson et al., 2021). Researchers and practitioners have since been encouraged to select an index that reflects the nature of the task and identifies both the magnitude and direction of asymmetry (Bishop et al., 2016, 2020a; Dos'Santos et al., 2021; Parkinson et al., 2021). The interpretation of asymmetry using arbitrary thresholds, such as 10-15%, has also been widely debated due to the poor evidence base supporting their use and the subject-, metric- and task-specific nature of asymmetry (Bishop, 2021; Parkinson et al., 2021). Instead, an individual approach to the interpretation of asymmetry scores has more recently been adopted, which utilises sample-specific thresholds and individual variability to detect meaningful differences between limbs within a task (Bishop, 2021; Dos'Santos et al., 2021). Therefore, it is essential that an individual approach to threshold selection is adopted to identify true asymmetry and make appropriate conclusions for research and practice.

Jump testing has become standard practice in applied settings for monitoring training and rehabilitation effects on inter-limb differences; however, only a handful of studies have examined both the magnitude and direction of asymmetry in longitudinal data (Bishop et al., 2020b, 2021c, 2022c; Fort-Vanmeerhaeghe et al., 2021). No differences were reported in the magnitude of asymmetry between timepoints across an athletic season for the unilateral drop jump or HJ, yet reduced performance and increased jump height asymmetry (Bishop et al., 2021c; Fort-Vanmeerhaeghe et al., 2021) were observed in the CMJ at mid-season compared to at least one other timepoint (Bishop et al., 2021c; Fort-Vanmeerhaeghe et al., 2021). This highlights the task specific nature of asymmetry and suggests the CMJ may be a more sensitive tool to detect fluctuations in asymmetry over time. However, high variability in the direction of asymmetry may give a false impression of longitudinal consistency (Bishop et al., 2020b, 2021c, 2022c; Fort-Vanmeerhaeghe et al., 2021). Moreover, longitudinal findings are often drawn from small samples of male athletes. As such, the effect of sex and sport in longitudinal data is not well understood, with only one of the previously identified articles recruiting both males and females across sports (Fort-Vanmeerhaeghe et al., 2021). Furthermore, athletes are commonly assessed once within each mesocycle (pre-, mid- and end-season) and so, introducing additional testing sessions may provide greater insight into longitudinal fluctuations. Therefore, the purpose of this research study was to investigate seasonal variation in jump performance and inter-limb asymmetry magnitude and direction in male and female athletes from different team sports.

7.3 Methods

7.3.1 Experimental Design

A repeated measures design was used to assess jumping performance and inter-limb asymmetries amongst university-level athletes at four timepoints across the British University & Colleges Sport (BUCS) season. Vertical and horizontal jump tests were performed both bilaterally and unilaterally twice during preseason (preseason 1 in August/September and preseason 2 in September/October) and twice during the competition season (competition 1 in November/December and competition 2 in February/March). Testing was completed at the university laboratory and each participant attended all 2-hour testing sessions at approximately the same of day throughout the study.

7.3.2 Participants

Thirty-eight young healthy team-sport athletes from basketball, hockey and netball completed this study (**Table 7.1**). All participants were recruited from the Performance teams at Nottingham Trent University which included athletes competing at university, national and international standards (see Section 4.3). Independent factors were explored in two independent analyses as it was not possible to recruit a large and varied enough sample to conduct a three-way analysis between time, sex and sport. A priori power analysis using G*Power (Version 3.1, University of Dusseldorf, Germany) identified 36 participants were required for a two-group analysis (sex) and 30 participants were required for a three-group analysis (sport) to achieve a statistical power of 0.8 and a type 1 alpha level of 0.05. Training data for the recruited sample was provided by the coaching team by completion of a training report form (Appendix 3, A3.1), at each testing timepoint. Programming goals remained the same across groups at each timepoint with a shift in focus from improving physical fitness in preseason to improving sport-specific performance in the competition phase (**Table 7.2**). Routine training and competition differed between teams across the season, but a general decrease in training load (**Table 7.3** and **Table 7.4**) and increase in competition (**Table 7.5** and **Table 7.6**) was observed from early preseason to the end of the competition phase. Written informed consent was provided by all participants and ethical approval was granted by the University's Human Invasive Ethics Committee (ID: 1535801, version 1.0, dated: 19/07/2022).

Table 7.1 Participant characteristics for the study sample

	Total (*n* = 38)	**Males (*n* = 21)**	**Females (*n* = 17)**	**Basketball (*n* = 12)**	**Hockey (*n* = 16)**	**Netball (*n* = 10)**
Age (years)	20.11 ± 1.35	20.33 ± 1.24	19.82 ± 1.47	20.75 ± 1.42	20.00 ± 1.26	19.50 ± 1.18
Height (m)	1.78 ± 0.11	1.84 ± 0.08	1.71 ± 0.09	1.87 ± 0.08	1.74 ± 0.09	1.74 ± 0.07
Body mass (kg)	77.63 ± 12.65	85.14 ± 9.37	68.36 ± 9.76	87.88 ± 10.08	74.09 ± 12.49	71.00 ± 7.91
Sex/Sport (*n*)	-	B = 10 H = 11 N = 0	B = 2 H = 5 N = 10	M = 10 F = 2	M = 11 F = 5	M = 0 F = 10
Level (*n*)	L1 = 5 L2 = 14 L3i =19	L1 = 3 L2 = 7 L3 = 11	L1 = 2 L2 = 7 L3 = 8	L1 = 0 L2 = 8 L3 = 4	L1 = 4 L2 = 1 L3 = 11	L1 = 1 L2 = 5 L3 = 4

N.B. body mass is the average value across all four timepoints. B = basketball, H = hockey, N = netball, M = males, F = females, L1 = international, L2 = national, L3 = university

7.3.3 Procedures

Prior to testing, participants completed a standardised warm-up consisting of jogging, dynamic stretches (e.g., walking lunges, hamstring sweeps, side lunges), sprinting and acceleration/decelerations, followed by three practice trials of each jump test. Upon completion of the warm-up, participants were re-introduced to the testing procedures (see Section 4.6.1) and were permitted additional practice trials for each test before maximal effort testing. A Vicon motion capture system (Nexus v2.14, Vicon Motion Systems Ltd, Oxford, UK) was used to collect kinetic data from an embedded multiaxial dual force plate system (AMTI, Watertown, MA, USA) sampling at 1000 Hz. Participants were instructed to stand upright with their hands positioned on the hips and feet positioned in the centre of each force platform. For unilateral tests, participants were instructed to flex the free knee to approximately 90° and avoid swinging the free limb during the trial. To encourage maximal effort, participants were allowed to land on one or two feet regardless of the nature of the task. Three maximal effort trials were conducted, separated by one minute of rest between trials, with the CMJ performed first followed by the HJ. Tests were completed bilaterally and then on alternating legs during unilateral tests, with the right limb tested first. Unsuccessful trials were repeated following a 60 s rest period. Instructions for the task were the same at all four timepoints and consistent feedback was provided to ensure proper technique.

Table 7.2 Training purpose for each team at four testing timepoints throughout the season

	Preseason 1	Preseason 2	Competition 1	Competition 2
Basketball (Men's)	Fitness	Combination	Sport Specific	Sport Specific
Basketball (Women's)	Fitness	Combination	Sport Specific	Sport Specific
Hockey (Men's)	Fitness	Combination	Sport Specific	Sport Specific
Hockey (Women's)	Fitness	Combination	Sport Specific	Sport Specific
Netball	Fitness	Combination	Sport Specific	Sport Specific

Table 7.3 Training frequency for each team at four testing timepoints throughout the season

	Preseason 1	Preseason 2	Competition 1	Competition 2
Basketball (Men's)	8	7	5	4
Basketball (Women's)	6	6	4	4
Hockey (Men's)	5	5	5	4
Hockey (Women's)	5	6	5	4
Netball	5	5	4	3

Table 7.4 Training duration (mins) for each team at four testing timepoints throughout the season

	Preseason 1	Preseason 2	Competition 1	Competition 2
Basketball (Men's)	>60-90	>60-90	>60-90	45-60
Basketball (Women's)	>60-90	>60-90	>60-90	45-60
Hockey (Men's)	>60-90	>60-90	>60-90	45-60
Hockey (Women's)	>60-90	>60-90	>60-90	45-60
Netball	>60-90	>60-90	>60-90	45-60

Table 7.5 Match frequency for each team at four testing timepoints throughout the season

	Preseason 1	Preseason 2	Competition 1	Competition 2
Basketball (Men's)	0	1	1	>1
Basketball (Women's)	0	1	1	>1
Hockey (Men's)	0	>1	>1	>1
Hockey (Women's)	0	>1	>1	>1
Netball	0	1	1	1

Table 7.6 Match duration (mins) for each team at four testing timepoints throughout the season

	Preseason 1	Preseason 2	Competition 1	Competition 2
Basketball (Men's)	0	48	48	75
Basketball (Women's)	0	48	48	60
Hockey (Men's)	0	70	70	75
Hockey (Women's)	0	70	70	75
Netball	0	60	60	60

7.3.3.1 Countermovement Jump

Participants were directed to squat down to a self-selected depth and rapidly explode upwards to achieve maximal height without excessively flexing the hips or knees during flight or on landing. A trial was considered successful if there was no excessive flexion of the hips or knees during the airborne phase, hands remained on the hips throughout, and an extended landing was adopted. Jump height was calculated using the flight-time method (Moir, 2008) due to its feasibility in applied practice (see Section 4.6.2), with take-off and landing defined as the instants when vertical force crossed a threshold equal to five times the standard deviation of the vertical force during the first 300 ms of flight (Chavda et al., 2019; McMahon et al., 2018)

7.3.3.2 Horizontal Jump

Participants were instructed to stand with the toes directly behind the start line and jump as far as possible to achieve maximal distance. A trial was considered successful if the first landing foot did not move after contact with the ground and hands remained on the hips throughout. Participants were asked to complete additional trials if their jump distance improved by more than 10 cm between trials. Jump distance was measured with a tape measure from the start line at take-off to the heel of the first landing foot (see Section 4.6.2).

7.3.4 Statistical Analysis

All data were extracted unfiltered and subsequently copied into a custom-made spreadsheet for analysis following guidance from (Chavda et al., 2020; McMahon et al., 2018). Means and standard deviations from the two best trials were recorded and analysed in SPSS (version 29.0 for Windows, Armonk, NY: IBM Corp). Normality was assessed using boxplots and the Shapiro-Wilk test which identified some performance and asymmetry variables as non-normally distributed (p < 0.05). All data were subsequently log transformed for analysis, with asymmetry data transformed using $log_{10}(ABS(n) + 1)$ due to the presence of negative scores in the dataset. Within-session reliability data were computed for the two best trials at each timepoint using the coefficient of variation (CV) intraclass correlation (ICC) for absolute agreement with 95% confidence intervals (CI) was conducted (see Section 4.8.2).

Inter-limb asymmetries were quantified to detect both asymmetry magnitude and direction between right and left limbs (see Section 4.8.3, Equation 3). The mean of the two best trials was used to compute an asymmetry index score (ASI) for unilateral jump tests at each timepoint. Interpretation of ASI scores was conducted in relation to the individual's test CV at the timepoint in question, as asymmetries that exceed individual variability can be considered 'real' (Dos'Santos et al., 2021). Additionally, sample-specific thresholds were established to identify individuals with "small to moderate" and "high to extreme" asymmetries, using the population mean + smallest worthwhile change (SWC; 0.2 × between-subject SD) and population mean + SD (1.0 × between-subject SD), respectively. Kappa coefficients were calculated to determine the levels of agreement in the direction of asymmetry (i.e., how consistently the right or left limb was favoured) between timepoints/tests, which goes undetected when using absolute asymmetry scores in traditional statistical analyses (see Section 4.8.3).

A two-way mixed design analysis of variance (ANOVA) was conducted to determine differences in log transformed performance data and asymmetry scores between time points and sexes, with statistical significance set at $p < 0.05$. A second two-way mixed design ANOVA was conducted in the same way to determine differences between timepoints and sports. The magnitude of change for group level comparisons was calculated according to recommendations for small sample sizes (Lakens, 2013) using a corrected effect size (Hedges, *g*) with 95% confidence intervals (see Section 4.8.4).

7.4 Results

All tests and groups showed excellent within-session ICC values and acceptable CV values (< 10%) at each timepoint (Appendix 5, **Table A5.1** and **Table A5.2**). Mean jump performance and interlimb asymmetry magnitude (directionless) at each timepoint are presented at the group level in **Table 7.7** and **Table 7.8**, with accompanying effect sizes and confidence intervals on the log-transformed data in Appendix 5 (**Table A5.3** and **Table A5.4**). Asymmetry thresholds determined from the population mean + SWC (small to moderate) and population mean + SD (high to extreme) are presented in **Table 7.9**, alongside the number of athletes who exceeded the threshold as well as their individual CV.

7.4.1 Sex Effects Across the Season

There was a significant interaction between time and sex for the bilateral CMJ ($p = 0.018$). Jump height in females increased significantly at competition-1 compared to preseason-1 but there were no significant changes over time in males. On average, females jumped 2 cm higher during the competition phase compared to preseason, whereas males jumped 1 cm lower. There was also a significant main effect of sex for the bilateral, right and left limb CMJ (all $p < 0.001$), with males jumping significantly higher than females at all four timepoints. On average, males jumped 9 cm higher than females in the bilateral HJ and 5 cm higher in both the right and left limb HJ (**Table 7.7**).

Table 7.7 Performance and inter-limb asymmetry (absolute values) during bilateral and unilateral jumping in male (n = 21) and female (n = 17) athletes at four timepoints throughout the season (mean ± SD)

Test/Timepoint	**Countermovement Jump**		**Horizontal Jump**	
Bilateral (m)	**Males**	**Females**	**Males**	**Females**
Preseason 1	$0.38 \pm 0.07^{\mathbf{F}}$	$0.28 \pm 0.04^{C1,\mathbf{M}}$	$1.85 \pm 0.21^{C1,C2,\mathbf{F}}$	$1.56 \pm 0.14^{\mathbf{M}}$
Preseason 2	$0.38 \pm 0.07^{\mathbf{F}}$	$0.29 \pm 0.03^{\mathbf{M}}$	$1.91 \pm 0.23^{\mathbf{F}}$	$1.56 \pm 0.13^{\mathbf{M}}$
Competition 1	$0.37 \pm 0.07^{\mathbf{F}}$	$0.30 \pm 0.04^{P1,\mathbf{M}}$	$1.93 \pm 0.21^{P1,\mathbf{F}}$	$1.61 \pm 0.12^{\mathbf{M}}$
Competition 2	$0.38 \pm 0.08^{\mathbf{F}}$	$0.29 \pm 0.05^{\mathbf{M}}$	$1.95 \pm 0.22^{P1,\mathbf{F}}$	$1.60 \pm 0.12^{\mathbf{M}}$
Unilateral: R (m)				
Preseason 1	$0.20 \pm 0.03^{\mathbf{F}}$	$0.15 \pm 0.03^{\mathbf{M}}$	$1.60 \pm 0.19^{C1,\mathbf{F}}$	$1.34 \pm 0.15^{\mathbf{M}}$
Preseason 2	$0.20 \pm 0.04^{\mathbf{F}}$	$0.15 \pm 0.03^{\mathbf{M}}$	$1.63 \pm 0.19^{C1,\mathbf{F}}$	$1.39 \pm 0.13^{\mathbf{M}}$
Competition 1	$0.20 \pm 0.04^{\mathbf{F}}$	$0.16 \pm 0.02^{\mathbf{M}}$	$1.73 \pm 0.18^{P1,P2,\mathbf{F}}$	$1.40 \pm 0.13^{\mathbf{M}}$
Competition 2	$0.20 \pm 0.04^{\mathbf{F}}$	$0.15 \pm 0.03^{\mathbf{M}}$	1.68 ± 0.20^{F}	$1.40 \pm 0.12^{\mathbf{M}}$
Unilateral: L (m)				
Preseason 1	0.20 ± 0.05^{F}	0.15 ± 0.04^{M}	1.59 ± 0.27^{F}	1.32 ± 0.15^{M}
Preseason 2	$0.20 \pm 0.04^{\mathbf{F}}$	$0.15 \pm 0.03^{\mathbf{M}}$	$1.65 \pm 0.20^{C1,\mathbf{F}}$	$1.33 \pm 0.16^{C1,\mathbf{M}}$
Competition 1	0.20 ± 0.04^{F}	0.16 ± 0.02^{M}	$1.72 \pm 0.17^{P2,\mathbf{F}}$	$1.40 \pm 0.11^{P2,\mathbf{M}}$
Competition 2	$0.20 \pm 0.05^{\mathbf{F}}$	$0.15 \pm 0.03^{\mathbf{M}}$	$1.67 \pm 0.17^{\mathbf{F}}$	$1.39 \pm 0.12^{\mathbf{M}}$
Unilateral: ASI (%)				
Preseason 1	9.79 ± 9.25	9.11 ± 6.67	6.53 ± 9.58	5.25 ± 4.04
Preseason 2	5.86 ± 4.10	8.62 ± 6.43	3.51 ± 2.31	6.01 ± 5.50
Competition 1	7.42 ± 7.28	6.41 ± 5.16	2.98 ± 2.69	3.29 ± 2.74
Competition 2	8.08 ± 7.90	8.60 ± 8.70	3.87 ± 2.68	4.15 ± 3.12

N.B significance at the p<0.001 level is bold and significance at the p<0.05 level is shown in plain text. R = right limb, L = left limb, ASI = asymmetry index, ^{P1} = Significantly different from preseason-1 (within group), ^{P2} = Significantly different from preseason-2 (within group), ^{C1} = Significantly different from competition-1 (within group), ^{C2} = Significantly different from competition-2 (within group), ^{M} = Significantly different from males (within timepoint), ^{F} = Significantly different from females (within timepoint)

There was no interaction between time and sex for any HJ variation but there was a significant main effect of time in the bilateral ($p < 0.001$), right ($p < 0.001$) and left limb HJ ($p = 0.005$). Jump distance in males increased significantly during the competition phase (1 and/or 2) compared to preseason (1 and/or 2) in all three HJ variations. Jump distance in females increased significantly at competition-1 compared to preseason-2 in the left limb HJ but there were no significant changes over time in the bilateral or right limb HJ. There was also a significant main effect of sex for the bilateral, right and left limb HJ (all $p < 0.001$), with males jumping significantly further than females at all four timepoints. On average, males jumped 33 cm, 28 cm and 30 cm further than females in the bilateral, right and left limb HJ, respectively (**Table 7.7**).

No significant interactions or differences were observed for time or sex on CMJ asymmetry and there was no significant interaction between time and sex for HJ asymmetry. There was a significant main effect of time on HJ asymmetry ($p = 0.029$); however, pairwise comparisons did not reveal any significant differences between timepoints (**Table 7.7**).

7.4.2 Sport Effect Across the Season

There was a significant interaction between time and sport for the bilateral CMJ ($p = 0.013$). Jump height in netballers increased significantly at competition-2 compared to preseason (1 and 2) but there were no significant changes over time in basketball or hockey athletes. On average, netballers jumped 1cm higher during the competition phase compared to preseason, whereas basketballers jumped 1cm lower and hockey athletes remained consistent. There was also a significant main effect of sport in the bilateral ($p = 0.029$) and right limb CMJ ($p = 0.017$). Basketballers jumped significantly higher than netballers in the bilateral CMJ at preseason (1 and 2) and in the right limb CMJ at preseason (1 and 2) and competition-1. On average, basketballers jumped 10 cm and 5 cm higher than netballers in the bilateral and right limb HJ, respectively (**Table 7.8**).

There was no interaction between time and sport for any HJ variation but there was a significant main effect of time in the bilateral ($p < 0.001$), right ($p < 0.001$) and left limb HJ ($p = 0.004$). Jump distance increased significantly during the competition phase (1 or 2) compared to preseason-1 in the bilateral HJ amongst hockey athletes and in the right limb HJ amongst basketballers but no significant changes over time were observed amongst netballers. There was also a significant main effect of sport in the bilateral ($p <$

0.001), right (p = 0.001) and left limb HJ (p = 0.006). Basketball athletes jumped significantly further than netball athletes at all four timepoints in the bilateral and right limb HJ and from preseason-2 onwards in the left limb HJ. On average, basketballers jumped 36 cm, 30 cm and 30 cm further in the bilateral, right and left limb HJ, respectively. Hockey athletes also jumped significantly further than netballers at all four timepoints in the bilateral HJ, at preseason-1 and competition-2 in the right limb HJ, and at competition-1 in the left limb HJ. On average, hockey athletes jumped 24 cm, 20 cm and 19 cm further in the bilateral, right and left limb HJ, respectively (**Table 7.8**).

No significant interactions or differences were observed for time or sport on CMJ asymmetry and there was no significant interaction between time and sport for HJ asymmetry. There was a significant main effect of time on HJ asymmetry (p = 0.019), with netballers demonstrating significantly reduced asymmetry at competition-1 (2.58 ± 2.67%) compared to preseason-2 (6.94 ± 5.93%) but basketballers and hockey athletes demonstrated no significant changes over time (**Table 7.8**).

Table 7.8 Performance and inter-limb asymmetry (absolute values) during bilateral and unilateral jumping in basketball (*n* = 12), hockey (*n* = 16) and netball (*n* = 10) athletes at four timepoints throughout the season (mean ± SD)

Test/Timepoint	Countermovement Jump			Horizontal Jump		
Bilateral (m)	**Basketball**	**Hockey**	**Netball**	**Basketball**	**Hockey**	**Netball**
Preseason 1	0.38 ± 0.09[N]	0.33 ± 0.06	0.28 ± 0.04[C2,B]	1.87 ± 0.24[**N**]	1.73 ± 0.19[C2,N]	1.51 ± 0.12[**B**,H]
Preseason 2	0.38 ± 0.09[N]	0.33 ± 0.06	0.29 ± 0.02[C2,B]	1.88 ± 0.29[N]	1.79 ± 0.23[N]	1.53 ± 0.10[B,H]
Competition 1	0.37 ± 0.08	0.33 ± 0.06	0.30 ± 0.03	1.94 ± 0.25[**N**]	1.81 ± 0.20[N]	1.58 ± 0.12[**B**,H]
Competition 2	0.38 ± 0.10	0.33 ± 0.08	0.31 ± 0.04[P1,P2]	1.93 ± 0.27[**N**]	1.82 ± 0.20[P1,N]	1.58 ± 0.13[**B**,H]
Unilateral: R (m)						
Preseason 1	0.20 ± 0.04[N]	0.18 ± 0.04	0.15 ± 0.03[B]	1.59 ± 0.24[C1,N]	1.51 ± 0.18[N]	1.31 ± 0.16[B,H]
Preseason 2	0.20 ± 0.04[N]	0.18 ± 0.03	0.15 ± 0.02[B]	1.65 ± 0.23[N]	1.51 ± 0.17	1.40 ± 0.14[B]
Competition 1	0.20 ± 0.05[N]	0.18 ± 0.03	0.16 ± 0.02[B]	1.74 ± 0.22[P1,**N**]	1.58 ± 0.20	1.40 ± 0.14[**B**]
Competition 2	0.20 ± 0.05	0.17 ± 0.04	0.16 ± 0.03	1.69 ± 0.25[**N**]	1.57 ± 0.17[N]	1.37 ± 0.11[**B**,H]
Unilateral: L (m)						
Preseason 1	0.20 ± 0.06	0.17 ± 0.04	0.15 ± 0.04	1.55 ± 0.35	1.50 ± 0.21	1.33 ± 0.14
Preseason 2	0.20 ± 0.05	0.17 ± 0.04	0.15 ± 0.02	1.65 ± 0.27[N]	1.51 ± 0.19	1.32 ± 0.15[B]
Competition 1	0.20 ± 0.05	0.17 ± 0.03	0.16 ± 0.02	1.71 ± 0.23[N]	1.59 ± 0.18[N]	1.40 ± 0.13[B,H]
Competition 2	0.20 ± 0.06	0.18 ± 0.05	0.16 ± 0.02	1.65 ± 0.24[N]	1.56 ± 0.17	1.39 ± 0.09[B]
Unilateral: ASI (%)						
Preseason 1	10.67 ± 10.56	8.34 ± 6.33	9.89 ± 7.88	8.41 ± 12.41	4.48 ± 3.24	5.39 ± 4.10
Preseason 2	6.90 ± 2.98	5.30 ± 4.62	10.19 ± 7.48	3.75 ± 3.55	3.83 ± 2.84	6.94 ± 5.93[C1]
Competition 1	9.81 ± 8.23	5.02 ± 4.05	6.67 ± 6.19	3.61 ± 3.16	3.09 ± 2.38	2.58 ± 2.67[P2]
Competition 2	11.80 ± 11.80	8.21 ± 5.72	4.28 ± 3.82	4.84 ± 3.41	3.99 ± 2.67	2.98 ± 2.28

N.B significance at the p<0.001 level is bold and significance at the p<0.05 level is shown in plain text. R = right limb; L = left limb; ASI = asymmetry index, [P1] = Significantly different from preseason-1 (within group), [P2] = Significantly different from preseason-2 (within group), [C1] = Significantly different from competition-1 (within group), [C2] = Significantly different from competition-2 (within group), [B] = Significantly different from basketball (within timepoint), [H] = Significantly different from hockey (within timepoint), [N] = Significantly different from netball (within timepoint)

Table 7.9 Inter-limb asymmetry thresholds and classification for study population using sample-specific thresholds and individual within-session CV values (*n* = 38)

	Countermovement Jump		**Horizontal Jump**	
	"Small to moderate" (*n*)	"High to extreme" (*n*)	"Small to moderate" (*n*)	"High to extreme" (*n*)
Preseason 1	11.11% (5)	17.58% (4)	7.47% (6)	13.52% (2)
Preseason 2	8.17% (6)	12.47% (6)	5.46% (9)	8.81% (4)
Competition 1	8.24% (5)	13.32% (6)	3.36% (6)	5.80% (6)
Competition 2	9.94% (8)	16.47% (3)	4.56% (8)	6.84% (5)

n = number of athletes whose asymmetry score exceeded their individual CV% and the specified threshold

7.4.3 Directional Consistency

For the direction of asymmetry between timepoints, levels of agreement in the whole sample ranged from poor to substantial in the CMJ (-0.20-0.80) and HJ (-0.40-0.80; **Table 7.10; Table 7.11**). Resultantly, 25 (65.8%) and 23 (60.5%) athletes from the study sample switched between their right and left limb over the course of testing in the CMJ and HJ, respectively (**Figure 7.1** and **Figure 7.2**).

Table 7.10 Kappa coefficients and descriptive levels of agreement for the changes in asymmetry direction between timepoints for vertical and horizontal jumping in male (*n* = 21) and female (*n* = 17) athletes

	Countermovement Jump		**Horizontal Jump**	
	Males	**Females**	**Males**	**Females**
Pre1 to Pre2	0.61 (substantial)	0.19 (slight)	0.39 (fair)	0.27 (fair)
Pre1 to Comp1	0.05 (slight)	0.33 (fair)	-0.04 (poor)	0.28 (fair)
Pre1 to Comp2	0.42 (moderate)	0.38 (fair)	0.34 (fair)	0.52 (moderate)
Pre2 to Comp1	0.26 (fair)	-0.07 (poor)	0.15 (slight)	0.14 (slight)
Pre2 to Comp2	0.39 (fair)	0.07 (slight)	0.53 (moderate)	0.39 (fair)
Comp1 to Comp2	0.26 (fair)	-0.03 (poor)	0.24 (fair)	0.76 (substantial)

Pre = preseason, Comp = competition phase

For direction of asymmetry between tests, levels of agreement in the sample ranged from slight to moderate at preseason-1 (0.13-0.46), poor to fair at preseason-2 (-0.02-0.40), poor to slight at competition-1 (-0.05-0.41), and slight to substantial at competition-2 (0.15 to 0.67; **Table 7.12**). Resultantly, 13 (34.2%), 15 (39.5%), 16 (42.1%) and 11 (28.9%) athletes from the study sample switched limbs between tests at each of the four timepoints, respectively (**Figure 7.1** and **Figure 7.2**).

Table 7.11 Kappa coefficients and descriptive levels of agreement for the changes in asymmetry direction between timepoints for vertical and horizontal jumping in basketball (*n* = 12), hockey (*n* = 16) and netball (*n* = 10) athletes

	Countermovement Jump			**Horizontal Jump**		
	Basketball	**Hockey**	**Netball**	**Basketball**	**Hockey**	**Netball**
Pre1 to Pre2	0.80 (substantial)	0.24 (fair)	0.20 (slight)	0.31 (fair)	0.38 (fair)	0.55 (moderate)
Pre1 to Comp1	0.40 (fair)	-0.02 (poor)	0.20 (slight)	0.03 (slight)	0.00 (poor)	0.40 (fair)
Pre1 to Comp2	0.33 (fair)	0.39 (fair)	0.52 (moderate)	0.17 (slight)	0.38 (fair)	0.80 (substantial)
Pre2 to Comp1	0.29 (fair)	-0.02 (poor)	0.20 (slight)	0.35 (fair)	0.13 (slight)	0.00 (poor)
Pre2 to Comp2	0.50 (moderate)	0.15 (slight)	0.20 (slight)	0.50 (moderate)	0.49 (moderate)	0.40 (fair)
Comp1 to Comp2	0.33 (fair)	0.15 (slight)	-0.20 (poor)	0.17 (slight)	0.63 (substantial)	0.60 (moderate)

Pre = preseason, Comp = competition phase

Table 7.12 Kappa coefficients and descriptive levels of agreement for the changes in asymmetry direction between vertical and horizontal jumping at each timepoint in males (*n* = 21) and females (*n* = 17), and basketball (*n* = 12), hockey (*n* = 16) and netball (*n* = 10)

	Preseason 1	**Preseason 2**	**Competition 1**	**Competition 2**
Group by sex				
Male	0.23 (fair)	0.19 (slight)	-0.05 (poor)	0.34 (fair)
Female	0.46 (moderate)	0.14 (slight)	0.41 (fair)	0.53 (moderate)
Group by sport				
Basketball	0.47 (moderate)	0.27 (fair)	0.12 (slight)	0.67 (substantial)
Hockey	0.13 (slight)	-0.02 (poor)	0.13 (slight)	0.15 (slight)
Netball	0.44 (moderate)	0.40 (fair)	0.20 (slight)	0.60 (moderate)

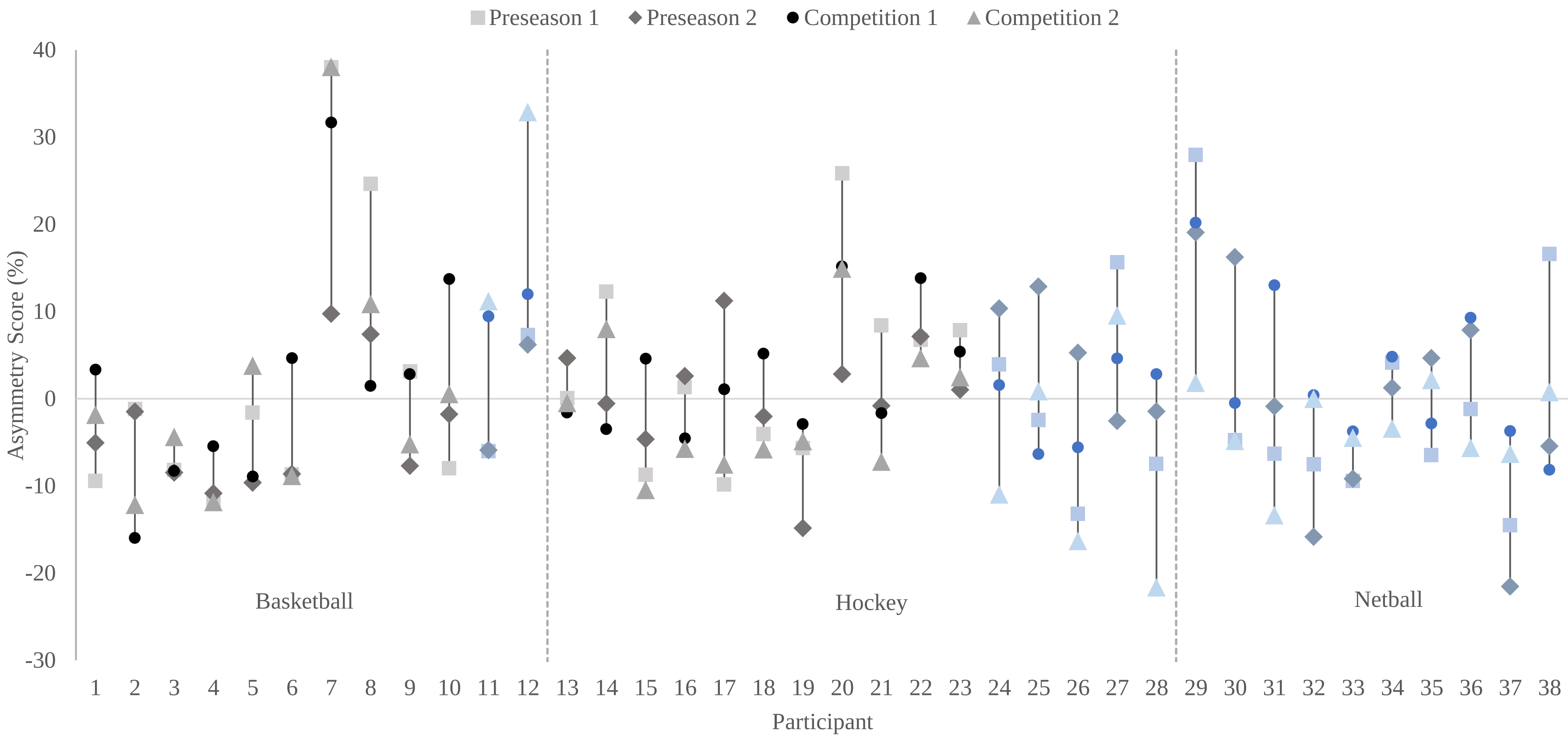

Figure 7.1 Individual asymmetry scores for jump height during the unilateral countermovement jump at four timepoints throughout the season. Males are identified in grey and females in blue. Positive values indicate right-limb dominance in the task and negative values indicate left-limb dominance

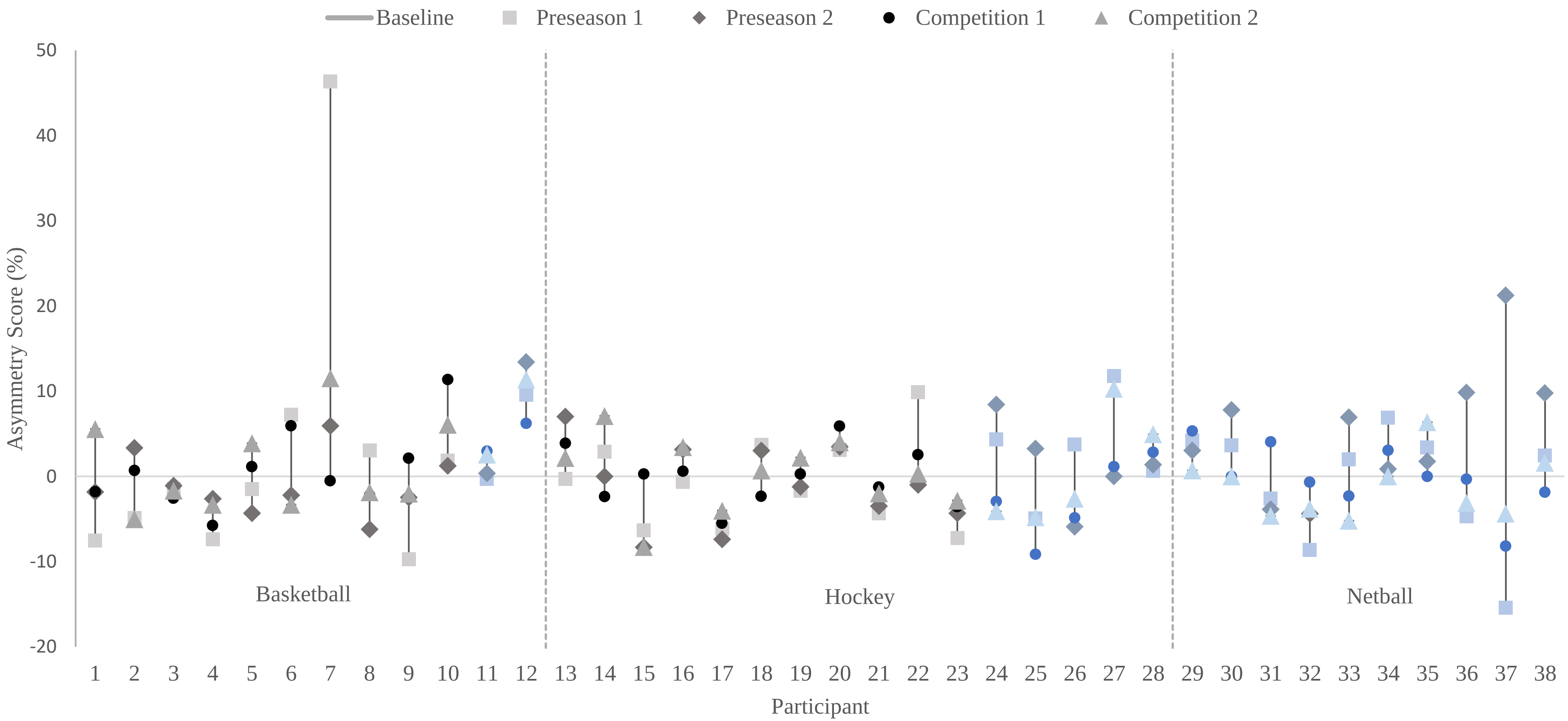

Figure 7.2 Individual asymmetry scores for jump distance during the unilateral horizontal jump at four timepoints throughout the season. Males are identified in grey and females in blue. Positive values indicate right-limb dominance in the task and negative values

7.5 Discussion

The present study aimed to investigate seasonal variation in jump performance and inter-limb asymmetry magnitude and direction in male and female athletes from various team sports. There was a significant interaction between time and sex, and time and sport for the bilateral CMJ. Females demonstrated an increase in jump height from preseason to competition phase testing, but male basketball and hockey athletes did not exhibit any changes in jump height over the season. There were no significant changes in unilateral CMJ performance or CMJ asymmetry with respect to time. However, HJ performance tended to improve over the season which coincided with a 3% reduction in HJ asymmetry across the sample from preseason 1 to competition 1. Despite individual variability, the magnitude of mean asymmetry remained largely consistent throughout the season and no significant sex or sport differences were observed. The direction of asymmetry, however, varied considerably in both the CMJ and HJ such that over 60% of the study sample switched which limb they favoured over the course of the season (**Table 7.10** and **Table 7.11**; **Figure 7.1** and **Figure 7.2**). Furthermore, levels of agreement for the direction of asymmetry between tests ranged from slight to moderate, with the most inconsistencies (42%) exhibited at competition-1 (**Table 7.12**).

Significant improvements in the bilateral and unilateral HJ were observed in the sample from preseason to the competition phase, which indicates enhanced force generation in the horizontal direction (**Table 7.7**; **Table 7.8**). Improvements following strength and power training are expected (Cormie et al., 2009, 2010a, 2010c; Jakobsen et al., 2012) and so, weaker jump performance at the start of preseason may be attributed to reduced training load during the summer period. Sports often encompass a variety of movement patterns which are influenced by the sport-specific environment, thus improvements specific to horizontal direction may indicate greater exposure to horizontal-oriented tasks (Manouras et al., 2016). Basketball, netball and hockey are all sports which require frequent sagittal plane movements, yet seasonal improvements in HJ performance were only evident amongst basketball and hockey athletes (**Table 7.8**). Seasonal improvements in vertical but not horizontal jumping amongst netballers indicate insufficient training stimulus in the horizontal direction. Individual differences have previously been observed in relation to positional demands, with midcourt athletes who are exposed to more frequent running and sprinting, demonstrating faster sprinting and change of direction capabilities than defenders who engage in more vertical-oriented activities, such as guarding and interceptions (Chandler et al., 2014; Fox et al., 2013; Graham et al., 2019). Therefore, positional characteristics may also contribute to variability in training effects on jump performance between sports and could partly explain larger adaptations in the horizontal direction in the current sample.

Males consistently performed better than females during both bilateral and unilateral variations of the CMJ and HJ (**Table 7.7**). Specifically, males jumped 19-26% higher and 15-19% further than females over the season in the CMJ and HJ, respectively. Sex disparities in jumping capacity can be largely explained by differences in muscle architecture, as males possess thicker muscles with longer fascicle lengths which increases force-production and power output (Alegre et al., 2009; Mangine et al., 2014). Displacement of the body's centre of mass before CMJ take-off has been shown to differ between sexes, with increased squat depth in males contributing to increased jump height (McMahon et al., 2017c). As velocity is defined as displacement divided by time, greater displacement of the centre of mass by increasing squat depth over the same amount of time results in a faster take-off velocity. Males also demonstrate a larger concentric net impulse which contributes to a faster centre of mass velocity at take-off and thereby, greater jump height due to the impulse-momentum relationship (Kirby et al., 2011; McMahon et al., 2017c). In the current study, larger improvements in HJ performance (raw and when normalised to height) were also observed amongst males over the season (**Table 7.7**). Jump distance in males improved by 10-13 cm from preseason to competition phase testing compared to their female counterparts who improved by 5-8 cm. Females may, therefore, benefit from adopting a more compliant leg strategy as well as utilising resistance and plyometric training which have been shown to improve strength and power capabilities (Aagaard et al., 2002; Cormie et al., 2009, 2010a, 2010b, 2010c; Jakobsen et al., 2012; Widrick et al., 2002; Wilson et al., 2012).

Differences were observed between sports in the current study, with basketball and hockey athletes outperforming netball athletes across several tasks and timepoints (**Table 7.8**). Specifically, basketball athletes jumped 19-26% higher and 15-20% further than netball athletes over the season in the CMJ and HJ, respectively. Hockey athletes also outperformed netball athletes in both jump tasks, jumping 6-17% higher and 11-15% further than netball athletes over the season in the CMJ and HJ, respectively. Sport effects observed here cannot be interpreted independently from sex due to the sex bias within groups, as males comprised a larger proportion of basketball (83%) compared to hockey

(69%), and netball was comprised solely of females. Differences in jump height between sports have, however, been captured previously for the CMJ and explained in relation to variable jump strategies (Chalitsios et al., 2019; Laffaye et al., 2014). Firstly, Laffaye et al., (2014) observed force-dominant profiles amongst outdoor athletes (soccer and baseball) who typically perform more explosive skills, whereas indoor athletes (basketball and volleyball) displayed more time-dominant profiles. Similarly, Chalitsios et al., (2019) reported increased jump height in soccer athletes due to increased countermovement depths, whereas basketball athletes displayed the ability to develop force quickly to enhance stretch-shortening function. Therefore, improved jump performance in basketball athletes from the current study may reflect enhanced jump strategy and muscle characteristics in relation to sport and training type.

The magnitude of mean asymmetry, in both vertical and horizontal jumping, remained largely consistent between timepoints, with absolute scores between 6.9-9.5% and 3.1-6.0% in the CMJ and HJ, respectively (**Table 7.7**; **Table 7.8**). Despite larger asymmetry scores and thresholds, as well as more individuals demonstrating "high to extreme" asymmetry in vertical jumping, it was the HJ that identified the only significant difference in asymmetry (**Table 7.9**). This may be partly explained by within-test variability, as larger CVs were observed over the season for the CMJ (1.5-6.6%) compared to the HJ (0.9-3.6%; Appendix 5, **Table A5.1** and **Table A5.2**). This indicates jump height calculated by the flight-time method may lack sufficient sensitivity to detect changes in asymmetry over time. Consequently, relatively large absolute changes in CMJ asymmetry between timepoints may go undetected while the HJ is able to detect smaller absolute changes in asymmetry. The HJ may, therefore, offer a more robust method of assessment in the absence of a force plate system. Reduced HJ asymmetry during the competition phase also coincided with improved HJ performance (**Table 7.7**; **Table 7.8**) which illudes to the negative relationship between jump performance and asymmetry found previously (Bishop et al., 2021c; Fort-Vanmeerhaeghe et al., 2020). Longitudinal fluctuations in asymmetry have also been documented in the literature, with larger asymmetries at midseason explained in relation to match congestion and reduced training (Bishop et al., 2021c; Fort-Vanmeerhaeghe et al., 2021). Therefore, targeted training, such as unilateral training involving double loading the weaker limb, may be recommended to improve unilateral jump performance and reduce inter-limb asymmetries, particularly during periods of match congestion when weaker performance is observed (Bishop et al., 2018b; Gonzalo-Skok et al., 2019).

The overall lack of significant differences in CMJ and HJ asymmetry between timepoints and trivial to small effect sizes for all but one timepoint comparison (-0.39 to 0.34) may initially suggest consistency in asymmetry over the season (**Table 7.7**; **Table 7.8**). Large SDs relative to the mean, however, indicate considerable variability in the sample, which suggests meaningful differences may be overlooked. This can partly be explained by variability in the direction of asymmetry as determined by kappa coefficients, which represent how consistently the same limb is favoured across repeated measures (**Table 7.10**; **Table 7.11**). At the whole sample level, levels of agreement ranged from slight to moderate in both the CMJ (-0.20-0.80) and HJ (-0.40-0.80) across the season, but with no observable pattern to these fluctuations over time. As a result, although the magnitude of asymmetry may appear consistent, variability in the direction of asymmetry could mean the favoured limb is subsequently outperformed by the same magnitude. One participant, for example, displayed the same magnitude of asymmetry at both competition phase timepoints; however, the right limb was favoured at competition-1 (+13%) and the left limb was favoured at competition-2 (-13%). Levels of agreement in the current study were generally higher than reported previously (Fort-Vanmeerhaeghe et al., 2021), yet this could be a result of differences in testing frequency and participant characteristics. Specifically, Fort-Vanmeerhaeghe et al., (2021), tested youth athletes (aged 14-18 yrs.) at three timepoints between September-May, whereas this study tested university aged athletes (aged 18-23 yrs.) at four timepoints between August-March. Directional inconsistencies were also observed between tasks, such that > 30% of the group did not favour the same limb in both tests at three out of four timepoints (**Table 7.12**). This is in accordance with the literature on vertical and horizontal jumping (Bishop et al., 2020a, 2021a; Fort-Vanmeerhaeghe et al., 2021), with higher levels of agreement expected for tasks with similar movement characteristics. However, kappa values indicate better directional consistency in the current study which could reflect increased task complexity when landing is less prescriptive, as the ability to manipulate jumping strategy before take-off becomes more challenging (Bishop et al., 2022b).

Despite the usefulness of this research, some limitations should be considered when interpreting its findings. Firstly, a more diverse sample of sporting backgrounds, which include varying degrees of cyclic and acyclic movements may reveal additional findings, specifically relating to jumping asymmetry (Kalata et al., 2020). There was also a strong sex bias within basketball and netball, meaning sport effects could not be interpreted in isolation from sex effects. An additional testing session was adopted by the current study than has been documented previously (Bishop et al., 2020b, 2021c, 2022c; Fort-Vanmeerhaeghe et al., 2021); however, due to scheduling constraints some athletes were tested much earlier within each mesocycle than others. It was beyond the scope of this research to investigate the effect of player position or experience level over time; however, future work should aim to assess seasonal fluctuations on a more individual basis in relation to player characteristics and training/match load. In addition, the current investigation aimed to adopt methods that can be easily implemented in an applied environment. However, kinetic analyses would provide greater insight into jump strategy and performance that cannot be achieved using performance metrics, such as jump height and distance. Lastly, log transformation was performed to address non-normality of the data, yet this requires values to be larger than zero and so, asymmetry scores were analysed as absolute values. Although kappa coefficients provide a measure of asymmetry direction, analysis of asymmetry magnitude without direction may, in part, be responsible for the lack of significant differences in asymmetry over time.

7.6 Conclusion

Improvements in horizontal jumping were observed over the season, which establishes the utility of horizontal jump distance in detecting longitudinal fluctuations in jumping performance amongst male and female team-sport athletes. The lack of improvements in vertical jump performance over the athletic season may reflect weak training stimuli in the vertical direction as well as poor measurement sensitivity when using the flight-time method to assess jump height. Future investigations should, therefore, aim to establish whether CMJ height determined by the take-off velocity method is more suitable for longitudinal monitoring. Mean inter-limb asymmetry remained largely consistent throughout the season, yet lower HJ asymmetry was observed during the competition phase, and this coincided with improved HJ performance. This highlights the importance of targeted training, particularly during periods of match congestion and reduced training load. Fluctuations in HJ, but not CMJ asymmetry, over time accompanied by higher within-session reliability also indicate the HJ may be a more robust method of assessment for inter-limb asymmetry. The direction of asymmetry was highly variable between timepoints and tests, which may explain the lack of differences in asymmetry magnitude over the season. Future research investigating seasonal fluctuations in vertical and horizontal jump performance and inter-limb asymmetry amongst team-sport athletes is warranted; however, it is essential asymmetry direction is monitored to avoid the illusion of consistency in asymmetry magnitude due to variability in its direction.

Chapter 8: General Discussion

8.1 Introduction

The various components of muscular strength are fundamental to human movement and athletic performance, influencing power, speed, endurance and overall functionality. Limb differences in muscular strength are likely to arise as a result of increased exposure to acyclic tasks in sport; however, inter-limb asymmetry is often considered to be harmful, with evidence to suggest increasing asymmetries could be detrimental to performance and injury risk. As such, the assessment of muscular strength and inter-limb asymmetry are of critical importance in athlete monitoring, yet variability in methodological practices have resulted in confusing and contradictory results. With no clear approach for optimal assessment using lab- or field-based methods, interpretation of results and decision-making is also challenging. The current research aimed to address these gaps by exploring various assessment methods and assessing their utility for the improved assessment and longitudinal monitoring of muscular strength and inter-limb asymmetry. By enhancing our understanding of muscular strength and inter-limb asymmetry, strategies can be implemented to improve athletic performance, reduce injury risks and optimise rehabilitation protocols, ultimately contributing to the advancement of sport and athletic performance.

This chapter aims to synthesise the findings of this research to discuss the methodological approaches used for the assessment of maximum and functional strength, as well their associated inter-limb asymmetries (Chapter 3 and Chapter 5), and to interrogate their utility for the assessment of cross-sectional and longitudinal monitoring in athletes (Chapter 6 and Chapter 7). The methods adopted for this research are also reviewed, with the limitations and potential improvements identified. Finally, the implications of this work are discussed, with recommendations for future research also provided.

8.2 Results Summary

8.2.1 Methods of Assessment for Strength Inter-Limb Asymmetry

The systematic review detailed in Chapter 3 was designed to identify methods adopted in the literature for the assessment of asymmetries in strength-related metrics. Accurate measurement and reporting of strength and inter-limb asymmetry are imperative to ensure appropriate conclusions can be made to inform the decision-making process. The review search identified 3,594 articles, of which 53 articles met the eligibility criteria and their methods were summarised according to 1) strength testing method, 2) asymmetry index, and 3) asymmetry threshold.

8.2.1.1 *Strength Testing Method*

Included articles adopted various methods to assess inter-limb asymmetry across maximum, functional and explosive components of strength. The gold-standard method, isokinetic dynamometry, was used by almost 50% (N = 25) of the articles, which was surpassed only by jumping and hopping tests which were implemented by 53% (N = 28) of studies. Widespread use of isokinetic dynamometry for the assessment of strength asymmetry can be expected considering its ability to make accurate and reliable measurements of peak torque from isometric and isokinetic testing conditions (de Araujo Ribeiro Alvares et al., 2015; Maffiuletti et al., 2007; Tsiros et al., 2011). However, the prevalence of functional jump/hop testing highlights the necessity for field-based alternatives to the gold-standard which is often unfeasible in the applied environment. Other tests were implemented less frequently within the literature; however, developments in techniques and procedures in functional methods are likely to enhance their uptake in more recent and future practice. Functional tests, such as jumping/hopping and multi-joint strength testing, offer useful alternatives to maximal effort testing that may be considered less fatiguing and more ecologically valid than laboratory-based methods. Despite this, the use of gold-standard methods should generally be encouraged to improve the quality and robustness of results and reporting. As such, the methodology associated with isokinetic dynamometry should be appropriately considered in lieu of the time and financial barriers that are influential in many research decisions.

8.2.1.2 *Asymmetry Index*

Twelve index types were identified by the review; however, indexes were often referred to by various names and in some cases, the nomenclature was contradictory to its numerical derivation which is cause for confusion in the literature. Distinction between limbs also varied across the identified articles, with five different limb comparisons identified. The most used index, referred to in the review as Index-1, was applied across all five limb comparisons yet, the index demonstrates disparate scores dependent on which limb was the better performing of the two. This is a limitation of all index calculations which require selection of a reference limb (Indexes 1-8), particularly when the selection is arbitrary, such as right/left where there is no obvious choice. However, disparities in the literature regarding strength between limbs also raises concern when applying other limb comparisons, as the reference limb (e.g., dominant or uninjured limb) may not always be stronger (Fältström et al., 2017; Fort-Vanmeerhaeghe et al., 2015, 2016). Using a stronger/weaker distinction can overcome the limitations of selecting a reference limb by dependably selecting the better performing limb as the denominator. This approach enables each index to produce the same magnitude of asymmetry, irrespective of which limb was the better performing of the two. However, the direction of asymmetry is lost by the calculation and so, must be interpreted alongside the raw data. The remaining four indexes (9-12) were immune to the limitations associated with selecting a reference limb, with each index individually producing the same magnitude of asymmetry irrespective of which limb was the better performing of the two. Disconcertingly, none of the indexes produced the same magnitude of asymmetry, with scores differing by up to almost 30% for the hypothetical example (limb values of 1.2 $Nm.kg^{-1}$ and 0.8 $Nm.kg^{-1}$). Thus, investigators should avoid indexes that require selection of a reference limb and comparison across index types is cautioned against. The index should also reflect the research context as some indexes are potentially better suited to specific task variations due to their mathematical design. Specifically, Index-9, in which the maximum value serves as the denominator, is suited to unilateral tasks whereas, Index-10, which uses the sum of both limb values as the denominator, has been suggested for bilateral tasks due to the contribution of both limbs to performance (Bishop et al., 2018a).

8.2.1.3 Asymmetry Threshold

Thirty of the included articles referred to asymmetry scores in terms of a threshold with the majority (N = 27) adopting an asymmetry threshold between 10-15% to interpret asymmetry magnitude. This range is frequently used because asymmetries exceeding 10-15% have been linked to higher injury risk and reduced performance (Bishop et al., 2019d, 2019b, 2021b; Brumitt et al., 2013; Croisier et al., 2008; Fort-Vanmeerhaeghe et al., 2020, 2022). Although fifteen articles implemented a pre-determined threshold within their study design, only three provided or referenced original evidence for the use of the adopted approach. An example of original evidence is a study by Barber et al., (1990) which was cited several times across the identified articles. A threshold of 85% symmetry (or 15% asymmetry) was established by the authors following a battery of functional tests in individuals with ACL-deficient knees treated non-operatively and healthy controls. More than 90% of the control group exhibited limb symmetry of ≥ 85% in horizontal hopping compared to only 50% of the ACL-deficient group, giving rise to the 15% threshold. Abnormal asymmetry scores (> 15%) across tests were also significantly correlated to subjectively reported limitations in running, sprinting, jumping/landing and twisting/cutting, indicating the potential implications of inter-limb symmetry below 85%. However, the other investigated tests were unable to identify any such threshold, with more than 90% of the ACL-deficient group demonstrating normal asymmetry (< 15%) in the shuttle run and a large proportion of both healthy and injured participants demonstrating abnormal asymmetry (> 15%) in the vertical jump. Furthermore, the asymmetry index described divides the involved limb value by the uninvolved limb value and multiplies it by 100, but the limb distinction for healthy group was not provided. As such, it is not possible to know whether the index was applied correctly as the calculation requires selection of a reference limb which becomes problematic if the denominator is not the better performing of the two limbs. Task-, metric- and population-sensitivity have also been evidenced, such that variability in asymmetry magnitude should be expected across various measures and samples (Bishop et al., 2019c, 2019b; Dos'Santos et al., 2017c; Read et al., 2021). Thus, even when a threshold is evidence-based it may be a poor diagnostic tool for the interpretation of asymmetry due to methodological flaws and poor generalisability. Alternatively, some investigations ($n = 3$) adopted a threshold based on the performance of the sample using the smallest worthwhile change (mean + 0.2 SD) to identify small to moderate asymmetries or the mean + 1SD to detect more extreme asymmetries (Dos'Santos et al., 2017b, 2018c; Lockie et al., 2014). In addition, the coefficient of variation is used to detect individuals who exceed their own individual variability, such that asymmetries can be interpreted as meaningful and real. Such methods overcome the limitations associated with pre-determined thresholds and are tailored to the testing procedures and population in question, which is necessary for appropriate decision-making.

The findings of the systematic review informed methodological decisions for the research conducted in Chapters 5-7 to ensure robust scientific practice for data collection and interpretation of results. Specifically, isokinetic dynamometry, jumping/hopping and multijoint strength testing were adopted for the assessment of maximum and functional strength, with the first two identified as the most common methods of assessment. Asymmetry was calculated from unilateral tasks using Index-9 due to its ability to overcome the limitations of selecting a reference limb whilst also being comparable to other indexes due to similarities in computational makeup. Finally, the direction of asymmetry was monitored using kappa coefficients and asymmetry scores were interpreted using sample specific thresholds to identify small-moderate and high-extreme asymmetries.

8.2.2 Optimisation of Dynamometry Protocols

8.2.2.1 Theoretical Approach

Although isokinetic dynamometry is recognised as the gold-standard method for measuring muscular strength, uptake is limited due to its association with strict technical procedures and lengthy experimental protocols that are not always feasible, particularly in an applied setting. Accordingly, Chapter 5 firstly aimed to investigate various measurement approaches for the assessment of isometric strength using dynamometry in a simulated dataset. To derive the data, torque-angle parameters (optimal angle, peak isometric torque and width) were retrieved for the knee, which is often considered easier to assess due to reduced degrees of freedom at the joint. Measurement protocols for the assessment of isometric knee flexion and knee extension strength were identified following a brief literature search (N = 50 articles). Although the focus of some investigations may not have been to determine maximum strength, it is relevant to demonstrate the potential error associated with the diversity of protocols implemented in the literature so that findings may inform future research decisions. The number and location of tested joint angles varied largely between protocols, with some measuring at a single joint angle (Bampouras et al., 2017; Blazevich et al., 2009b; Harridge et al., 1999; Konrad et al., 2021), whilst others measured joint torque at ten or more joint angles dispersed throughout the joint range of motion (Chow et al., 1999a; de Brito Fontana & Herzog, 2016).

To assess the effect of a single measurement angle approach, joint torque-angle profile variations were derived from the literature-sourced parameters and torque error (absolute difference between measured and original peak torque) was computed for commonly tested measurement angles for each joint action. The smallest torque error was observed at measurement angles of 150° (2.4 ± 2.8%) for the knee flexors and 240° (1.5 ± 1.4%) for the knee extensors, with 0% torque error for all torque-angle profile variations when the measurement angle and optimal angle coincided. Knee flexor and extensor torque error increased for measurement angles displaced further from the optimal angle, particularly for narrower torque-angle profiles. Thus, when attempting to measure maximum strength from peak torque at a single measurement angle, measurements must be made as close to the optimal angle as possible, particularly for profiles of the knee extensors which have a steeper drop-off from peak torque.

To assess the effect of a multiple measurement angle approach, submaximal random noise (-10 Nm threshold determined from experimental data) was introduced at measurement angles dispersed evenly throughout the torque-angle profile for each joint action (flexion = 10; extension = 9). All possible measurement combinations, with a minimum of three joint angles up to the maximum available in the joint range, were investigated and 'parameter error' was calculated as the RMS difference between predicted and original parameter values. Protocols with more measurement angles were associated with reduced parameter error, such that mean parameter errors were below 5% for all comparisons apart from knee flexor width (17.5%). This can, however, be attributed to the small magnitude of the knee flexor width parameter (bounds: 0.2-2.0) which is a scaling factor rather that a measurable unit and can be challenging to interpret independently of the modelled torque-angle profile. Instead, the distance from peak torque to the quadratic root (termed half range) revealed a mean parameter error for the knee flexors of 8.6% with more measurement angles, which provides a more intuitive interpretation for the effect of profile curvature on parameter prediction. Protocols with just three measurement angles resulted in the least accurate parameter predictions. However, smaller errors were generally observed for protocols which included a spread of measurement angles throughout the joint range, including an angle near the optimum.

8.2.2.2 Experimental Approach

As a continuation of the preliminary investigation in simulated data, the effect of measurement protocol on optimisation of torque-angle characteristics was subsequently investigated in experimental data (Chapter 5). Extensive protocols with up to nine or ten measurement angles are unlikely to be viable in applied practice, so a reduced protocol which could be completed within 1 hour (including anthropometric measures, 5-min warm-up, familiarisation, warm-up trials and maximal effort testing) was adopted for this aim. Joint torque was measured at five joint angles dispersed throughout the joint range of motion and all measurement combinations with a minimum of three angles up to the maximum available in the joint range were assessed. To assess the effect of the number and location of measurement angle, the RMS difference between measured and optimised torques was calculated throughout the torque-angle profile and maximum measured peak torque was compared to optimised peak torque (calculated as a percentage of the measured value and referred to as 'peak torque error'). The fitted data closely represented the measured data across measurement combinations with three to five joint angles, exhibiting average RMS differences < 1.5% for knee flexion and ≤ 2.1% for knee extension. The RMS difference in peak torque error across measurement combinations for the knee flexors and knee extensors was ≤ 8.3% and ≤ 6.7%, respectively, indicating optimised peak torque was overestimated compared to measured peak torque. However, this is a reflection of the weighting approach for the cost function, which gave a higher weighting to fitted data above the measured data. The weighting approach was selected to account for submaximal torque measurements of approximately -10 Nm in the experimental data. Torque representations varied with the location of measurement angles, but no observable pattern could be discerned between combinations which could indicate the effectiveness of the adopted five measurement positions.

Collectively, the findings indicate protocols with multiple measurement angles should be adopted for the assessment of knee flexor and knee extensor torque-angle characteristics, particularly when attempting to measure maximum strength from peak torque. However, in the interest of time, fewer measurement angles may be used to predict torque-angle characteristics if the protocol is optimised by including a spread of measurement angles throughout the joint range, including an angle near the optimum. Specifically, optimisation of torque-angle characteristics from protocols with five measurement angles dispersed throughout the joint range of motion are recommended. Although the concept of this work and the premise of its findings may be known within the research community, it serves to conceptualise the effect of various measurement strategies for the assessment of isometric strength characteristics. To the authors' knowledge, this is the first study to do so, and it can be used to inform gold-standard practices in the wider research and applied communities.

8.2.3 Reliability of Functional Tests

Although Chapter 5 proposes a selective measurement strategy that may be used to optimise torque-angle characteristics from dynamometry data in a time-efficient manner; technical and financial barriers are such that functional testing methods are still warranted. Previous research has demonstrated reliability is specific to the test, metric and population under investigation (Bishop et al., 2019c; Dos'Santos et al., 2018c; Guppy et al., 2019; Merrigan et al., 2022) and so, it is essential reliability is established amongst new samples and testing methods. Within-session reliability of bilateral and unilateral functional tests was investigated in a single session (Chapter 6) and across the season (Chapter 7) in team-sport athletes. All tests demonstrated acceptable absolute and good to excellent relative reliability, indicating their ability to detect differences in peak force and performance metrics that may be considered meaningful (Atkinson & Nevill, 1998; Bishop, 2021; Hopkins, 2000). The cross-sectional study (Chapter 6) investigated the unilateral IMTP, CMJ and HJ and found the HJ to be the most reliable test, evidenced by lower CVs (1.41-3.48%), higher ICCs (0.94-0.99), and narrower Bland-Altman limits of agreement (distance: 5%; PF: 12-16%), particularly for jump distance. Similarly, high reliability was observed in jump performance metrics (height and distance) across the season (Chapter 7) for unilateral and bilateral variations of the HJ and the bilateral CMJ, but larger variability was evident in the unilateral CMJ. Comparatively, better reliability in the unilateral HJ may be partly explained by methodology, as trials that improved by 10 cm or more were repeated to limit learning effects which would further reduce variability within the test. However, this would not explain equally high reliability in vertical and horizontal jumping when performed bilaterally. Instead, this finding likely reflects a more consistent performance strategy when a less prescriptive, double-leg landing is permitted for horizontal hopping, but this does not translate to vertical hopping. Seasonal data revealed more variability in the unilateral and bilateral HJ during preseason compared to the competition phase but the same was not observed for the CMJ. This indicates the CMJ may be less sensitive to detect differences in jump height calculated by both the flight-time (Chapter 7) or take-off velocity (Chapter 6) method. Peak force during the unilateral CMJ also exhibited better absolute and relative reliability than jump height, which reiterates CMJ height may not be an adequate measure to detect changes in functional performance between trials, tests, or limbs. The IMTP was not implemented in the longitudinal study, so it is not possible to comment on seasonal fluctuations or bilateral task performance. However, reliability from the cross-sectional study (Chapter 6) indicate both absolute and relative peak force from the unilateral IMTP to be highly reliable which is in accordance with the literature (Brady et al., 2018; Dos'Santos et al., 2017c, 2017d, 2018b; Guppy et al., 2022; Haff et al., 2005).

8.2.4 Strength and Inter-limb Asymmetry: Relationships between Maximum and Functional Tests

Despite the usefulness of field-based methods for measuring functional performance, the relationship between functional and maximum strength tests must be properly understood to ensure appropriate interpretation. Chapter 6 investigated the relationships between maximal isometric strength on the dynamometer and functional outcomes in the IMTP, CMJ and HJ. Significant positive relationships were found between maximum strength and two of the investigated functional strength tests. The coefficient of determination revealed ≤ 30% of the variance in each respective functional test could be accounted for by maximum strength and so, these findings may not be considered clinically meaningful. Nonetheless, it was surprising to observe a significant relationship between dominant knee flexor strength and IMTP peak force on both limbs since the IMTP relies predominantly on the extensors (Kuki et al., 2018; McMahon et al., 2015). Knee extensor strength on the non-dominant limb was positively related to HJ distance on the dominant limb which highlights the role of the knee extensors in horizontal propulsion. The relationship between dominant and non-dominant limbs was unexpected; however, this could reflect sport-specific adaptations related to function that do not necessarily reflect maximum strength. The sample investigated for this research were university-level hockey athletes, 87% of whom identified their right limb as the dominant limb. Thus, better functional strength on the dominant (mostly right) limb may be explained by adaptations due to limb preference, whereas better maximum strength on the non-dominant (mostly left) limb may be better explained by sport-specific task exposure. This could also explain poor to slight consistency in asymmetry direction across most tests and inter-limb differences that favoured the dominant limb in knee flexor strength but the non-dominant limb in the IMTP. Directional consistency between tests was lower compared to previous research in elite youth female soccer athletes during three different vertical jump tests (Bishop et al., 2020a). Disparities can likely be explained by participant characteristics and methodological differences; however, moderate directional consistency was observed between knee extension strength and HJ distance indicating some similarities between tasks. Significant relationships were also observed between HJ distance asymmetry and maximum knee strength of the dominant and non-dominant limb. As such, in the absence of an isokinetic dynamometer, the HJ could offer insight into inter-limb asymmetries in maximum knee extension strength. Lastly, positive relationships between inter-limb asymmetry and performance suggest stronger individuals exhibit larger asymmetries in maximum and functional strength, with significant relationships both within and between tests and metrics. Therefore, in some instances, improved strength may be synonymous with increasing asymmetries such that minimising inter-limb differences may not prove advantageous in the pursuit of optimal performance. Overall, the findings of this work demonstrate the complicated relationship between maximum and functional strength and inter-limb asymmetries such that tests may not be used interchangeably. However, stronger relationships and better directional consistency may be expected for tasks which have transferable components and similarities. Further investigation is required to better understand the relationships between maximum and functional strength and inter-limb asymmetries. Considering the weak relationships and variable nature of inter-limb asymmetry, researchers and practitioners should also consider the utility of alternative benchmarks for longitudinal tracking of performance and injury risk which do not involve comparative assessment between limbs.

8.2.5 Strength and Inter-limb Asymmetry: Longitudinal Monitoring in Athletes

The systematic review in Chapter 3 included investigations across a range of populations including, individuals who were injured or post-surgery, athletes, females and older individuals, as well as their healthy, sedentary, male and young counterparts. Some groups were less represented than others, with older individuals only studied by one of the identified articles. Females were under-represented compared to males (n = 25 and n = 44, respectively), and although over 62% of the articles recruited athletes of varying standards, most studies investigated a single sport, which limits the generalisability of findings to more diverse groups. Findings were inconsistent within- and between-groups, with reports of relative symmetry to asymmetries larger than 15% and both the presence and absence of associations between asymmetry and injury or performance. For instance, the presence of asymmetry of varying magnitudes amongst athletic samples indicates that it may not always be dysfunctional. Asymmetries of up to 15% in functional performance have also been observed in athletes without detriment to change of direction speed (Dos'Santos et al., 2017b, 2018c), yet contradictory reports exist (Bishop et al., 2019d; Coratella et al., 2018; Lockie et al., 2016; Madruga-Parera et al., 2020). However, improved function has been observed in injured individuals and ACLR patients who demonstrate reduced asymmetries (Bookbinder et al., 2020; Harput et al., 2018; Zwolski et al., 2015) which further complicates the notion of 'good' or 'bad' asymmetry. Disparate reports of asymmetries in male and females were also identified, with some reporting no differences in asymmetry between sexes (Lisee et al., 2019), yet others identified group differences in vertical jump asymmetries, with females exhibiting larger asymmetries than males (Fort-Vanmeerhaeghe et al., 2016).

Inconsistent findings in the literature may be partly attributed to the highly variable nature of asymmetry, such that asymmetry magnitude and direction varies across tests, metrics and participant characteristics (Bishop et al., 2019c, 2019b; Dos'Santos et al., 2017c; Read et al., 2021). As such, longitudinal testing using multiple assessment methods in diverse samples is warranted. Chapter 7 aimed to monitor functional strength and inter-limb asymmetry using simple, cost-effective field-based tests (CMJ and HJ) at four timepoints throughout an athletic season in male and female, team-sport athletes (basketball, hockey and netball). Males jumped higher and further than females at all four timepoints across unilateral and bilateral variations of the CMJ and HJ, which was expected due to optimal physiological characteristics and jump strategy reported in males (McMahon et al., 2017c). Sport effects were also observed, with basketballers outperforming netballers in both vertical and horizontal jumping at multiple timepoints throughout the season. Likewise, hockey athletes outperformed netballers in horizontal jump variations at multiple timepoints, although the same was not observed in vertical jumping. Interpretation of sport effects independently from sex was not possible as basketball and hockey were comprised mainly of males, whereas netball was comprised solely of females. Nonetheless, better performance amongst basketball athletes in vertical and horizontal jumping but only in horizontal jumping amongst hockey athletes likely reflects sport-specific adaptations as well as physiological predisposition. Specifically, basketball requires vertical plane activities for attacking and defensive play, whereas hockey is associated with larger total running distances (Taylor et al., 2017). Improvements in horizontal jumping were observed over time, with males, basketball, and hockey athletes demonstrating increased jump distance across tests and timepoints. On the other hand, females demonstrated increased jump distance for one test and timepoint comparison and netballers demonstrated no changes over the season. This suggests lack of training stimulus for improvements in horizontal jump performance, particularly amongst netballers which could be useful for informing training interventions in these athletes. Contrastingly, females and netballers demonstrated improvements in vertical jumping that were not observed in males, basketball, or hockey athletes.

Therefore, adaptations in jumping performance should be interpreted in relation to both the sport and sex of participants under investigation.

Larger inter-limb asymmetries were observed in vertical compared to horizontal jumping, with thresholds for “high to extreme” CMJ asymmetry between 13-18% compared to 6-14% for HJ asymmetry. Nonetheless, the CMJ failed to detect any changes in asymmetry over time or between groups. Fluctuations in HJ asymmetry were identified over the season, with netballers exhibiting reduced asymmetry in the competition phase compared to preseason testing. This coincided with non-significant improvements in unilateral performance on the left side, which was identified as the non-dominant limb by 100% of the netball athletes. Considering the HJ was also found to be more reliable in Chapter 6, it may offer a more effective tool for detecting meaningful differences between limbs and monitoring inter-limb asymmetry over time. However, it is also necessary to monitor the direction of asymmetry, as kappa coefficients revealed poor to substantial consistency both within and between the HJ and CMJ, which corroborates previous literature. Resultantly, an individual approach, which considers sample-specific thresholds and individual variability, is necessary to ensure appropriate interpretation of asymmetry.

8.3 Limitations

8.3.1 Data Simulation and Model Optimisation

The investigation of dynamometry protocols firstly adopted a theoretical approach in which hypothetical torque-angle data were simulated from parameters identified in the literature (Chapter 5). Only two articles provided a complete set of subject-specific torque-angle parameters for the knee joint and so, the exact errors reported in this research cannot be generalised to other investigations. Furthermore, the differences between experimentally measured and predicted torques suggest the investigated sample in Chapter 5 and Chapter 6 did not exert maximal torques during MVICs, despite experience of strength testing on the dynamometer. The magnitude of submaximal noise in the experimental data was estimated using a central difference approach to predict alternating torque measurements. The weighting approach also had to be tailored to consider the influence of submaximal measurements on model performance; however, it is not possible to know the exact magnitude of submaximal noise without obtaining true maximal data. The findings reflect these assumptions and so, generalisability is limited. Nonetheless, the conceptualisation of this problem is useful to the research community and provides a method for optimising torque-angle data using various measurement and prediction strategies. The effectiveness of the optimisation approach is expected to be improved when utilising data which are closer to maximal, which may be achieved following better familiarisation or electrical stimulation to derive the torque-angle profile. The current method assumed that the net moment, once corrected for gravitational effects, was equivalent to the maximum agonist moment, however increased antagonistic co-activation has been observed at longer antagonistic muscle lengths (Babault et al., 2003; Kubo et al., 2004). The contribution to joint torque from the antagonistic muscle may, therefore, be larger at the extremes of the range of motion which would influence the measured moment. Despite this, Bampouras et al., (2017) demonstrated no difference in knee extension MVC once corrected for antagonistic torque which indicates increased antagonistic activation at longer muscle lengths does not influence torque output. Rather, reduced net torque at the extremes of the range of motion can be accounted for by reduced neural activation at unfavourable agonist muscle lengths. Although the influence of co-activation may be of less consequence in the current investigation of the knee flexors and extensors, the same may not be said for other joint actions and contraction modes.

8.3.2 Data Collection and Participant Characteristics

Isometric knee strength was assessed using dynamometry; however, only a single measurement was made for each tested joint angle. Although isometric peak torque has been established as a reliable metric for strength testing (de Araujo Ribeiro Alvares et al., 2015; Maffiuletti et al., 2007; Tsiros et al., 2011) it would have been useful to investigate within-session reliability for dynamometry measures to allow for comparison with functional testing which involved multiple trials. An additional implication of this was the inability to calculate asymmetry thresholds as per recommendations which utilise the CV to identify individuals that exceed their own individual variability (Bishop, 2021; Dos'Santos et al., 2021). Asymmetry thresholds were calculated for functional tests in Chapter 6, and this would have allowed for additional comparisons between maximum strength tests compared to functional methods. The longitudinal research described in Chapter 7 monitored team-sport athletes across the season, but the sample size did not allow for a three-way ANOVA to be conducted between time, sex and sport. Instead, two separate two-way ANOVA were conducted to assess time and sex, and time and sport. The sex bias, such that males made up most of basketball and hockey and none of the netball group, also means that it is not possible to interpret the effect of sex and sport independently from one another. Lastly, a dominant/non-dominant limb comparison was used in Chapter 6 to avoid dilution of performance effects which can occur when using a right/left limb comparison (Dos'Santos et al., 2017b, 2018c; Jones & Bampouras, 2010; Newton et al., 2006). However, limb dominance was determined subjectively by each participant which can be problematic if the selection does not match performance (i.e., the 'dominant' limb does not outperform the 'non-dominant' limb). Instead, dominance may be determined objectively as the better performing limb in a task (Dos'Santos et al., 2017b, 2018c; Jones & Bampouras, 2010). Yet, this becomes challenging when comparing across tasks as the direction of asymmetry is known to fluctuate across repeated measures both within- and between-tests. The right/left comparison has been used previously to identify differences in maximum and functional strength (Parkinson et al., 2021) and was able to detect differences between groups and timepoints in Chapter 7. Stronger findings may, however, have been observed if a dominant/non-dominant limb comparison was adopted.

8.4 Future Research

Optimisation of torque-angle characteristics using different measurement approaches was addressed in an investigation of the knee flexors and knee extensors (Chapter 5). Exploring the effect of measurement approaches for other joints and joint actions is necessary to establish best practice for curve-fitting and modelling from dynamometry data. The recommended approach for selective protocols of the knee flexors and extensors may be somewhat generalisable. However, future directions should consider the effect of architectural and physiological characteristics on the torque-angle profile which could influence the effectiveness of specific measurement strategies. Future work should also aim to develop the application of optimisation techniques to increase their utility in wider research and applied environments.

The experimental research described in this thesis was conducted in young, male and female, university-level, team-sport athletes, yet a larger and more diverse sample would be recommended for future research. Athletes have been shown to demonstrate sport-specific adaptations that influence inter-limb differences in knee flexor and extensor strength, with 'asymmetrical' sports exhibiting larger asymmetries than 'symmetrical' or 'hybrid' sports (Kalata et al., 2020). Thus, investigations should explore performance and inter-limb asymmetries in maximum and functional strength between sports which include varying degrees of cyclic and acyclic movements. Longitudinal monitoring of athletes should also be conducted throughout the season including preseason, competition phase, and offseason testing to capture fluctuations in response to training. The incorporation of training and match load data would also prove insightful. Older individuals have been shown to demonstrate impaired physical function and increased fall incidence (Chon et al., 2018; McGrath et al., 2021; Portegijs et al., 2005; Skelton et al., 2002), but were under-represented in the literature. Thus, investigations in older individuals of sedentary and athletic status is also encouraged.

Although the use of performance metrics, such as jump height and distance, serve a purpose in the assessment of functional strength in a simple, quick and cost-effective manner, force plates offer greater insight into jump strategy and performance (McMahon et al., 2017b, 2017a). Force plate technology is becoming increasingly popular in the applied community, with automated processing designed to reduce the time and expertise required for data handling. Further research should, therefore, aim to determine inter-limb asymmetries using force plates and where possible, a twin force plate system is recommended to allow for limb-specific kinetic analyses during bilateral task performance.

8.5 Conclusion

The purpose of this thesis was to investigate the assessment of muscular strength and inter-limb asymmetry, with a specific focus on methodology that can be implemented in a field-based environment for athlete monitoring. Although numerous asymmetry indexes exist, only those which do not require the selection of a reference limb should be implemented in future investigations and comparison across indexes should be avoided. Pre-determined thresholds, such as the commonly adopted 10-15%, are somewhat arbitrary and unfounded. Instead, an individual approach to the interpretation of inter-limb asymmetry, which utilises sample-specific thresholds and individual variability, is recommended. Functional performance tests offer a useful diagnostic tool for the assessment of functional strength and inter-limb asymmetry; however, the relationships between functional and maximum strength testing remains unclear. As such, tests should not be used interchangeably. A battery of field-based tests is likely to be optimal in the assessment and longitudinal monitoring of functional strength and inter-limb asymmetry, and the use of force plates is likely to provide more insightful data. In instances where dynamometry is possible, estimations of torque-angle characteristics can be improved from selective protocols if the measurement approach is optimised. Specifically, isometric torque-angle measurements should be spread throughout the joint range and include a measurement angle near to the approximate optimal angle. Current recommendations offer an opportunity to improve methodological practices for the assessment and longitudinal monitoring of muscular strength and associated inter-limb asymmetries via laboratory and field-based methods.

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Chapter 10: Appendices

Appendix 1. Worked Index Examples

Table A1.1 Worked examples of hypothetical asymmetry scores for each index calculation across three scenarios: 1) limb symmetry, where A=B, 2) limb asymmetry, where A>B, or 3) limb asymmetry where A<B. Hypothetical peak torque values of 1.0Nm.kg^{-1}, 1.2Nm.kg^{-1} and 0.8Nm.kg^{-1} were used

Index Calculation	**Scenario**	**Limb Comparison**				
		Involved/Uninvolved	**Dominant/Nondominant**	**Right/Left**	**Stronger/Weaker**	**Stance/Skill**
1. $\frac{B}{A} \cdot 100$	1	$\frac{1.0}{1.0} \cdot 100 = 100\%$	$\frac{1.0}{1.0} \cdot 100 = 100\%$	$\frac{1.0}{1.0} \cdot 100 = 100\%$	$\frac{1.0}{1.0} \cdot 100 = 100\%$	$\frac{1.0}{1.0} \cdot 100 = 100\%$
	2	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$
	3	$\frac{1.2}{0.8} \cdot 100 = 150\%$	$\frac{1.2}{0.8} \cdot 100 = 150\%$	$\frac{1.2}{0.8} \cdot 100 = 150\%$	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$	$\frac{1.2}{0.8} \cdot 100 = 150\%$
2. $\frac{A}{B} \cdot 100$	1	$\frac{1.0}{1.0} \cdot 100 = 100\%$	$\frac{1.0}{1.0} \cdot 100 = 100\%$	$\frac{1.0}{1.0} \cdot 100 = 100\%$	$\frac{1.0}{1.0} \cdot 100 = 100\%$	$\frac{1.0}{1.0} \cdot 100 = 100\%$
	2	$\frac{1.2}{0.8} \cdot 100 = 150\%$	$\frac{1.2}{0.8} \cdot 100 = 150\%$	$\frac{1.2}{0.8} \cdot 100 = 150\%$	$\frac{1.2}{0.8} \cdot 100 = 150\%$	$\frac{1.2}{0.8} \cdot 100 = 150\%$
	3	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$	$\frac{1.2}{0.8} \cdot 100 = 150\%$	$\frac{0.8}{1.2} \cdot 100 = 66.7\%$
3. $\left[1 - \left(\frac{B}{A}\right)\right] \cdot 100$	1	$\left[1 - \left(\frac{1.0}{1.0}\right)\right] \cdot 100 = 0\%$	$\left[1 - \left(\frac{1.0}{1.0}\right)\right] \cdot 100 = 0\%$	$\left[1 - \left(\frac{1.0}{1.0}\right)\right] \cdot 100 = 0\%$	$\left[1 - \left(\frac{1.0}{1.0}\right)\right] \cdot 100 = 0\%$	$\left[1 - \left(\frac{1.0}{1.0}\right)\right] \cdot 100 = 0\%$
	2	$\left[1 - \left(\frac{0.8}{1.2}\right)\right] \cdot 100 = 33.3\%$	$\left[1 - \left(\frac{0.8}{1.2}\right)\right] \cdot 100 = 33.3\%$	$\left[1 - \left(\frac{0.8}{1.2}\right)\right] \cdot 100 = 33.3\%$	$\left[1 - \left(\frac{0.8}{1.2}\right)\right] \cdot 100 = 33.3\%$	$\left[1 - \left(\frac{0.8}{1.2}\right)\right] \cdot 100 = 33.3\%$
	3	$\left[1 - \left(\frac{1.2}{0.8}\right)\right] \cdot 100 = -50\%$	$\left[1 - \left(\frac{1.2}{0.8}\right)\right] \cdot 100 = -50\%$	$\left[1 - \left(\frac{1.2}{0.8}\right)\right] \cdot 100 = -50\%$	$\left[1 - \left(\frac{0.8}{1.2}\right)\right] \cdot 100 = 33.3\%$	$\left[1 - \left(\frac{1.2}{0.8}\right)\right] \cdot 100 = -50\%$

Table A1.2 Worked examples of hypothetical asymmetry scores for each index calculation across three scenarios: 1) limb symmetry, where A=B, 2) limb asymmetry, where A>B, or 3) limb asymmetry where A<B. Hypothetical peak torque values of 1.0Nm.kg^{-1}, 1.2Nm.kg^{-1} and 0.8Nm.kg^{-1} were used (*cont.)*

Index Calculation	Scenario	Limb Comparison				
		Involved/Uninvolved	**Dominant/Nondominant**	**Right/Left**	**Stronger/Weaker**	**Stance/Skill**
4. $100-\left[\left(\frac{B}{A}\right)\cdot 100\right]$	1	$100-\left[\left(\frac{1.0}{1.0}\right)\cdot 100\right]=0\%$	$100-\left[\left(\frac{1.0}{1.0}\right)\cdot 100\right]=0\%$	$100-\left[\left(\frac{1.0}{1.0}\right)\cdot 100\right]=0\%$	$100-\left[\left(\frac{1.0}{1.0}\right)\cdot 100\right]=0\%$	$100-\left[\left(\frac{1.0}{1.0}\right)\cdot 100\right]=0\%$
	2	$100-\left[\left(\frac{0.8}{1.2}\right)\cdot 100\right]=33.3\%$	$100-\left[\left(\frac{0.8}{1.2}\right)\cdot 100\right]=33.3\%$	$100-\left[\left(\frac{0.8}{1.2}\right)\cdot 100\right]=33.3\%$	$100-\left[\left(\frac{0.8}{1.2}\right)\cdot 100\right]=33.3\%$	$100-\left[\left(\frac{0.8}{1.2}\right)\cdot 100\right]=33.3\%$
	3	$100-\left[\left(\frac{1.2}{0.8}\right)\cdot 100\right]=-50\%$	$100-\left[\left(\frac{1.2}{0.8}\right)\cdot 100\right]=-50\%$	$100-\left[\left(\frac{1.2}{0.8}\right)\cdot 100\right]=-50\%$	$100-\left[\left(\frac{0.8}{1.2}\right)\cdot 100\right]=33.3\%$	$100-\left[\left(\frac{1.2}{0.8}\right)\cdot 100\right]=-50\%$
5. $\frac{100}{A}\cdot B\cdot(-1)+100$	1	$\frac{100}{1.0}\cdot 1.0\cdot(-1)+100=0\%$	$\frac{100}{1.0}\cdot 1.0\cdot(-1)+100=0\%$	$\frac{100}{1.0}\cdot 1.0\cdot(-1)+100=0\%$	$\frac{100}{1.0}\cdot 1.0\cdot(-1)+100=0\%$	$\frac{100}{1.0}\cdot 1.0\cdot(-1)+100=0\%$
	2	$\frac{100}{1.2}\cdot 0.8\cdot(-1)+100=33.3\%$	$\frac{100}{1.2}\cdot 0.8\cdot(-1)+100=33.3\%$	$\frac{100}{1.2}\cdot 0.8\cdot(-1)+100=33.3\%$	$\frac{100}{1.2}\cdot 0.8\cdot(-1)+100=33.3\%$	$\frac{100}{1.2}\cdot 0.8\cdot(-1)+100=33.3\%$
	3	$\frac{100}{0.8}\cdot 1.2\cdot(-1)+100=-50\%$	$\frac{100}{0.8}\cdot 1.2\cdot(-1)+100=-50\%$	$\frac{100}{0.8}\cdot 1.2\cdot(-1)+100=-50\%$	$\frac{100}{1.2}\cdot 0.8\cdot(-1)+100=33.3\%$	$\frac{100}{0.8}\cdot 1.2\cdot(-1)+100=-50\%$
6. $\frac{A}{B}$	1	$\frac{1.0}{1.0}=1$	$\frac{1.0}{1.0}=1$	$\frac{1.0}{1.0}=1$	$\frac{1.0}{1.0}=1$	$\frac{1.0}{1.0}=1$
	2	$\frac{1.2}{0.8}=1.5$	$\frac{1.2}{0.8}=1.5$	$\frac{1.2}{0.8}=1.5$	$\frac{1.2}{0.8}=1.5$	$\frac{1.2}{0.8}=1.5$
	3	$\frac{0.8}{1.2}=0.7$	$\frac{0.8}{1.2}=0.7$	$\frac{0.8}{1.2}=0.7$	$\frac{1.2}{0.8}=1.5$	$\frac{0.8}{1.2}=0.7$

Table A1.3 Worked examples of hypothetical asymmetry scores for each index calculation across three scenarios: 1) limb symmetry, where A=B, 2) limb asymmetry, where A>B, or 3) limb asymmetry where A<B. Hypothetical peak torque values of 1.0Nm.kg^{-1}, 1.2Nm.kg^{-1} and 0.8Nm.kg^{-1} were used (*cont.)*

Index Calculation	Scenario	Limb Comparison				
		Involved/Uninvolved	**Dominant/Nondominant**	**Right/Left**	**Stronger/Weaker**	**Stance/Skill**
7. $\frac{(A-B)}{A}\cdot 100$	1	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$
	2	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$
	3	$\frac{(0.8-1.2)}{0.8}\cdot 100 = -50\%$	$\frac{(0.8-1.2)}{0.8}\cdot 100 = -50\%$	$\frac{(0.8-1.2)}{0.8}\cdot 100 = -50\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(0.8-1.2)}{0.8}\cdot 100 = -50\%$
8. $\frac{(B-A)}{A}\cdot 100$	1	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$
	2	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$
	3	$\frac{(1.2-0.8)}{0.8}\cdot 100 = 50\%$	$\frac{(1.2-0.8)}{0.8}\cdot 100 = 50\%$	$\frac{(1.2-0.8)}{0.8}\cdot 100 = 50\%$	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$	$\frac{(1.2-0.8)}{0.8}\cdot 100 = 50\%$
9. $\frac{(A-B)}{Max(A,B)}\cdot 100$	1	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{1.0}\cdot 100 = 0\%$
	2	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$
	3	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$	$\frac{(1.2-0.8)}{1.2}\cdot 100 = 33.3\%$	$\frac{(0.8-1.2)}{1.2}\cdot 100 = -33.3\%$

Table A1.4 Worked examples of hypothetical asymmetry scores for each index calculation across three scenarios: 1) limb symmetry, where A=B, 2) limb asymmetry, where A>B, or 3) limb asymmetry where A<B. Hypothetical peak torque values of $1.0 Nm.kg^{-1}$, $1.2 Nm.kg^{-1}$ and $0.8 Nm.kg^{-1}$ were used *(cont.)*

Index Calculation	Scenario	Limb Comparison				
		Involved/Uninvolved	**Dominant/Nondominant**	**Right/Left**	**Stronger/Weaker**	**Stance/Skill**
10. $\frac{(A-B)}{(A+B)}\cdot 100$	1	$\frac{(1.0-1.0)}{(1.0+1.0)}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{(1.0+1.0)}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{(1.0+1.0)}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{(1.0+1.0)}\cdot 100 = 0\%$	$\frac{(1.0-1.0)}{(1.0+1.0)}\cdot 100 = 0\%$
	2	$\frac{(1.2-0.8)}{(1.2+0.8)}\cdot 100 = 20\%$	$\frac{(1.2-0.8)}{(1.2+0.8)}\cdot 100 = 20\%$	$\frac{(1.2-0.8)}{(1.2+0.8)}\cdot 100 = 20\%$	$\frac{(1.2-0.8)}{(1.2+0.8)}\cdot 100 = 20\%$	$\frac{(1.2-0.8)}{(1.2+0.8)}\cdot 100 = 20\%$
	3	$\frac{(0.8-1.2)}{(0.8+1.2)}\cdot 100 = -20\%$	$\frac{(0.8-1.2)}{(0.8+1.2)}\cdot 100 = -20\%$	$\frac{(0.8-1.2)}{(0.8+1.2)}\cdot 100 = -20\%$	$\frac{(1.2-0.8)}{(1.2+0.8)}\cdot 100 = 20\%$	$\frac{(0.8-1.2)}{(0.8+1.2)}\cdot 100 = -20\%$
11. $\frac{[45-\tan^{-1}(B/A)]}{90}\cdot 100$	1	$\frac{[45-\tan^{-1}(1.0/1.0)]}{90}\cdot 100 = 0\%$	$\frac{[45-\tan^{-1}(1.0/1.0)]}{90}\cdot 100 = 0\%$	$\frac{[45-\tan^{-1}(1.0/1.0)]}{90}\cdot 100 = 0\%$	$\frac{[45-\tan^{-1}(1.0/1.0)]}{90}\cdot 100 = 0\%$	$\frac{[45-\tan^{-1}(1.0/1.0)]}{90}\cdot 100 = 0\%$
	2	$\frac{[45-\tan^{-1}(0.8/1.2)]}{90}\cdot 100 = 12.6\%$	$\frac{[45-\tan^{-1}(0.8/1.2)]}{90}\cdot 100 = 12.6\%$	$\frac{[45-\tan^{-1}(0.8/1.2)]}{90}\cdot 100 = 12.6\%$	$\frac{[45-\tan^{-1}(0.8/1.2)]}{90}\cdot 100 = 12.6\%$	$\frac{[45-\tan^{-1}(0.8/1.2)]}{90}\cdot 100 = 12.6\%$
	3	$\frac{[45-\tan^{-1}(1.2/0.8)]}{90}\cdot 100 = -12.6\%$	$\frac{[45-\tan^{-1}(1.2/0.8)]}{90}\cdot 100 = -12.6\%$	$\frac{[45-\tan^{-1}(1.2/0.8)]}{90}\cdot 100 = -12.6\%$	$\frac{[45-\tan^{-1}(0.8/1.2)]}{90}\cdot 100 = 12.6\%$	$\frac{[45-\tan^{-1}(1.2/0.8)]}{90}\cdot 100 = -12.6\%$
12. $\ln\left(\frac{B}{A}\right)\cdot 100$	1	$\ln\left(\frac{1.0}{1.0}\right)\cdot 100 = 0\%$	$\ln\left(\frac{1.0}{1.0}\right)\cdot 100 = 0\%$	$\ln\left(\frac{1.0}{1.0}\right)\cdot 100 = 0\%$	$\ln\left(\frac{1.0}{1.0}\right)\cdot 100 = 0\%$	$\ln\left(\frac{1.0}{1.0}\right)\cdot 100 = 0\%$
	2	$\ln\left(\frac{0.8}{1.2}\right)\cdot 100 = -40.5\%$	$\ln\left(\frac{0.8}{1.2}\right)\cdot 100 = -40.5\%$	$\ln\left(\frac{0.8}{1.2}\right)\cdot 100 = -40.5\%$	$\ln\left(\frac{0.8}{1.2}\right)\cdot 100 = -40.5\%$	$\ln\left(\frac{0.8}{1.2}\right)\cdot 100 = -40.5\%$
	3	$\ln\left(\frac{1.2}{0.8}\right)\cdot 100 = 40.5\%$	$\ln\left(\frac{1.2}{0.8}\right)\cdot 100 = 40.5\%$	$\ln\left(\frac{1.2}{0.8}\right)\cdot 100 = 40.5\%$	$\ln\left(\frac{0.8}{1.2}\right)\cdot 100 = -40.5\%$	$\ln\left(\frac{1.2}{0.8}\right)\cdot 100 = 40.5\%$

A = uninvolved, dominant, right, stronger, or stance limb value; B = involved, nondominant, left, weaker, or skill limb value

Appendix 2. Ethical Documentation

A2.1. Participant Information Sheet for Data Collection 1

Study title: Strength Asymmetry in Athletes (SAAS) – Longitudinal Testing

Brief summary

You are invited to participate in a study that will investigate between-limb asymmetries in strength amongst university-level athletes. Strength asymmetry refers to a lack of equality between two limbs (e.g., dominant vs non-dominant) or muscle groups (e.g., quadriceps vs hamstrings) in the ability to produce maximum force. This study will investigate the validity of field-based strength tests compared to the gold-standard measurement of strength, the isokinetic dynamometer. Strength asymmetries will also be studied across the course of the season to better understand how asymmetries may fluctuate with time for athletes from different sports.

Therefore, the aims of this research are to 1) **i**nvestigate the validity of field-based tests compared to the gold-standard, isokinetic dynamometer, when measuring strength asymmetry between limbs and 2) to identify typical asymmetry in athletes across various sports at multiple timepoints throughout the season.

What's involved?

Study requirements: You will be required to attend a total of four 2hr testing sessions for this study. Two testing sessions will take place during pre-season and the remaining two will take place during the competition phase. A subsample of participants will also complete an additional 45min testing session at the second timepoint during pre-season. For data collection, you are expected to wear tight clothing, and shoes which you would normally be comfortable wearing when partaking in exercise. You and your coach will be asked to provide information on your training and to report any injuries over the course of testing.

Testing restrictions: To be eligible for this study, you must fulfil the following criteria:

- Healthy male or female, aged between 18-35 yrs.
- No experience of musculoskeletal injury in the past 6 months or underlying neurological injury/condition
- Participating in a primary sport (regular, intense, year-round training primarily in one sport) which involves use of the lower limbs for at least one year

- Currently affiliated to a sports team which receives structured training delivered by qualified coaches and competes in the British University & Colleges Sport (BUCS) League or equivalent university-level league

What would taking part involve?

When you arrive: The investigator will explain what participation would involve, and how data obtained from participants will be stored securely and pseudo-anonymously. The procedures for documenting adverse/serious adverse events throughout the study will also be explained.

The investigator will also explain how data obtained in the research will be used and how you will be able to access any reports or publications based on this study. You should be aware that data obtained in this study could be used in research publications and conference presentations. If your data is included within these reports or publications, you will not be identifiable. Following completion of the study, you and your coach will be provided with an individualised athlete report based on your data which may be used for programming. This will include 3D scan and strength data.

Procedures for withdrawing yourself/your data from the study following trial completion will also be explained. You will have the opportunity to ask any questions/raise any concerns regarding taking part. If satisfied, you will be asked to complete an informed consent form and a health screen and history questionnaire.

Data collection: During your visits to the laboratory, you will undergo a complete assessment which will involve the following measurements:

- Anthropometric measurements (height, weight, 3D scanning)
- Isokinetic dynamometer (isometric knee flexion/extensions) *subsample at second visit only
- Isometric midthigh pull
- Countermovement jump
- Jump/hop for distance

After participation: After completion of the study, the investigator will reiterate how the data obtained will be used (e.g., research publications, conference presentations, feedback report), and procedures for withdrawing yourself/your data from the study following trial completion will also be repeated.

Participant responsibility
During the study period, you will be expected to report any injuries that are likely to affect your participation in the study. You may be withdrawn from the study if you sustain an injury that may affect your ability to complete the measures required. This will be decided by the research team following your completion of an injury report form.

You will be asked kindly to complete all documents accurately, and to follow the guidelines throughout the study. If completed accurately, the information from this study may help develop a better understanding of the application of these measures to performance enhancement and injury prevention strategies.

COVID Special measures
Given the current situation in the UK (and around the World) interactions between people from different households carries a risk of COVID-19 infection. The research team will ensure that testing is completed in line with government guidelines at the time. All facilities in which research is being conducted have been COVID-19 risk assessed. To mitigate any risks, all equipment will be sterilised before, during and after use with researchers maintaining good hand hygiene.

What are the possible benefits of taking part?
You and your coach will be provided with an individualised report based on your data which may be used to inform training and injury prevention strategies. The results of this study may also provide wider benefits by contributing to the body of knowledge on strength asymmetry which may be used to provide more effective support to athletes and other individuals.

What are the possible disadvantages and risks of taking part?
The sessions will be conducted in a suitable environment and involve tests which the participants are familiar with, therefore the risk is no greater than during anything encountered during normal training. Participants however may feel short of breath after maximal effort tests and although it is extremely unlikely, high intensity exercise has been known to reveal unsuspected heart or circulation problems and very rarely these have had serious or fatal consequences. Participants may also experience some delayed muscle soreness following each session.

Once I take part, can I change my mind? What will happen to my data?
Yes, after you have read this information and asked any questions you may have, you will be asked to complete an Informed consent form. However, if at any time, before, during, or after the sessions, you wish to withdraw your participation from the study, you can do so without having to specify a reason. If you do decide to withdraw from the study, any data collected will be destroyed. You will be able to withdraw your data up until the point when your data is written up (May 2023).

Will my data be kept confidential?
Nottingham Trent University will be using information from you in order to undertake this study and will act as the data controller for this study. This means that we are responsible for looking after your information and using it properly. Nottingham Trent University will keep identifiable information about you for 5 years or journal paper publications are complete. Following this, secure disposal of the data will be arranged by the Research Data Management Officer at Nottingham Trent University.

Your rights to access, change or move information are limited, as we need to manage your information in specific ways for the research to be reliable and accurate. If you withdraw from the study, your data will be deleted. To safeguard your rights, we will use the minimum personally identifiable information possible. Throughout the study all data will be coded, and a database containing personal identifying data will be stored securely. At the end of the study, feedback based on your asymmetry data will be shared with your coaching team. This database will be destroyed following the completion of the study and publication of journal articles.

This data will be used by NTU students who will also have access to and will use a proportion of the data to complete their project write-ups. They will assist with data collection and analysis whilst always under supervision.

What if I am not happy with how the research was conducted?
If you have any concerns regarding your participation in this study or the conduct of any of the investigators involved, please refer to the university policy relating to research misconduct:

https://www.ntu.ac.uk/__data/assets/pdf_file/0009/204300/procedure-for-investigating-alleged-research-misconduct.pdf

Who should I contact if I have further questions?

If you have any further questions/concerns, please contact the research team using the contact details below.

Principal Investigator	**Co-investigator**
Amy Parkinson Nottingham Trent University School of Science and Technology New Hall Block 178 Clifton Nottingham NG11 8NS Email: amy.parkinson@ntu.ac.uk	Dr Charlotte Apps Nottingham Trent University School of Science and Technology New Hall Block 168 Clifton Nottingham NG11 8NS Telephone: 01158 484831 Email: charlotte.apps@ntu.ac.uk

A2.2. Participant Information Sheet for Data Collection 2

Study title: Strength Asymmetry in Athletes (SAAS) – Preseason Testing

Brief summary

You are invited to participate in a study that will investigate between-limb asymmetries in strength amongst university-level athletes. Strength asymmetry refers to a lack of equality between two limbs (e.g., dominant vs non-dominant) or muscle groups (e.g., quadriceps vs hamstrings) in the ability to produce maximum force. This study will investigate the validity of field-based strength tests compared to the gold-standard measurement of strength, the isokinetic dynamometer. Strength asymmetries will also be studied across the course of the season to better understand how asymmetries may fluctuate with time for athletes from different sports.

Therefore, the aims of this research are to 1) investigate the validity of field-based tests compared to the gold-standard, isokinetic dynamometer, when measuring strength asymmetry between limbs and 2) to identify typical asymmetry in athletes across various sports at multiple timepoints throughout the season.

What's involved?

Study requirements: You will be required to attend a group familiarisation (1hr) and field-based testing session (2hrs) and an individual dynamometry session (1hr) during preseason. For data collection, you are expected to wear tight-fitting clothing (i.e., gym/cycling shorts and tank top), and shoes which you would normally be comfortable wearing when partaking in exercise. You and your coach will be asked to provide information on your training and to report any injuries over the course of testing.

Testing restrictions: To be eligible for this study, you must fulfil the following criteria:

- Healthy male or female, aged between 18-35 yrs.
- No experience of musculoskeletal injury in the past 6 months or underlying neurological injury/condition
- Participating in a primary sport (regular, intense, year-round training primarily in one sport) which involves use of the lower limbs for at least one year
- Currently affiliated to a sports team which receives structured training delivered by qualified coaches and competes in the British University & Colleges Sport (BUCS) League or equivalent university-level league

What would taking part involve?

Location: Room 005, CELS, Clifton Campus (Ground floor, along the corridor and to the right)

When you arrive: The investigator will explain what participation would involve, and how data obtained from participants will be stored securely and pseudo-anonymously. The procedures for documenting adverse/serious adverse events throughout the study will also be explained.

The investigator will also explain how data obtained in the research will be used and how you will be able to access any reports or publications based on this study. You should be aware that data obtained in this study could be used in research publications and conference presentations. If your data is included within these reports or publications, you will not be identifiable. Following completion of the study, you and your coach will be provided with an individualised athlete report based on your strength data which may be used for programming.

Procedures for withdrawing yourself/your data from the study following trial completion will also be explained. You will have the opportunity to ask any questions/raise any concerns regarding taking part. If satisfied, you will be asked to complete an informed consent form and a health screen and history questionnaire.

Data collection:

Familiarisation: During your first visit to the laboratory, you will be familiarised with a series of tests in preparation for the field-based session (tests listed below)

Field-based session: You will attend this session as a group (up to 4 participants). During the session, you will undergo a complete field-based assessment including the following measurements:

- Anthropometric measurements (height, weight, 3D scanning)
- Isometric midthigh pull
- Countermovement jump
- Jump/hop for distance

Isokinetic Dynamometry Session: You will attend this session individually and will complete a series of isometric (static) knee flexion/extensions on the isokinetic dynamometer.

After participation:

After completion of the study, the investigator will reiterate how the data obtained will be used (e.g., research publications, conference presentations, feedback report), and procedures for withdrawing yourself/your data from the study following trial completion will also be repeated.

Participant responsibility

During the study period, you will be expected to report any injuries that are likely to affect your participation in the study using the Injury Report Form. You may be withdrawn from the study if you sustain an injury that may affect your ability to complete the measures required. This will be decided by the research team following your completion of an injury report form.

You will be asked kindly to complete all documents accurately, and to follow the guidelines throughout the study. If completed accurately, the information from this study may help develop a better understanding of the application of these measures to performance enhancement and injury prevention strategies.

COVID Special measures

Given the current situation in the UK (and around the World) interactions between people from different households carries a risk of COVID-19 infection. The research team will ensure that testing is completed in line with government guidelines at the time. All facilities in which research is being conducted have been COVID-19 risk assessed. To mitigate any risks, all equipment will be sterilised before, during and after use with researchers maintaining good hand hygiene.

What are the possible benefits of taking part?

You and your coach will be provided with an individualised report based on your data which may be used to inform training and injury prevention strategies. The results of this study may also provide wider benefits by contributing to the body of knowledge on strength asymmetry which may be used to provide more effective support to athletes and other individuals.

What are the possible disadvantages and risks of taking part?

The sessions will be conducted in a suitable environment and involve tests which the participants are familiar with, therefore the risk is no greater than during anything encountered during normal training. Participants however may feel short of breath after maximal effort tests and although it is extremely unlikely, high intensity exercise has been known to reveal unsuspected heart or circulation problems and very rarely these have had serious or fatal consequences. Participants may also experience some delayed muscle soreness following each session.

Once I take part, can I change my mind? What will happen to my data?

Yes, after you have read this information and asked any questions you may have, you will be asked to complete an Informed consent form. However, if at any time, before, during, or after the sessions, you wish to withdraw your participation from the study, you can do so without having to specify a reason. If you do decide to withdraw from the study, any data collected will be destroyed. You will be able to withdraw your data up until the point when your data is written up (Dec 2023).

Will my data be kept confidential?

Nottingham Trent University will be using information from you in order to undertake this study and will act as the data controller for this study. This means that we are responsible for looking after your information and using it properly. Nottingham Trent University will keep identifiable information about you for 5 years or journal paper publications are complete. Following this, secure disposal of the data will be arranged by the Research Data Management Officer at Nottingham Trent University.

Your rights to access, change or move information are limited, as we need to manage your information in specific ways for the research to be reliable and accurate. If you withdraw from the study, your data will be deleted. To safeguard your rights, we will use the minimum personally identifiable information possible. Throughout the study all data will be coded, and a database containing personal identifying data will be stored securely. At the end of the study, feedback based on your asymmetry data will be shared with your coaching team. This database will be destroyed following the completion of the study and publication of journal articles.

This data will be used by NTU students who will also have access to and will use a proportion of the data to complete their project write-ups. They will assist with data collection and analysis whilst always under supervision.

What if I am not happy with how the research was conducted?

If you have any concerns regarding your participation in this study or the conduct of any of the investigators involved, please refer to the university policy relating to research misconduct:

https://www.ntu.ac.uk/__data/assets/pdf_file/0009/204300/procedure-for-investigating-alleged-research-misconduct.pdf

Who should I contact if I have further questions?

If you have any further questions/concerns, please contact the research team using the contact details below.

Principal Investigator	**Co-investigator**
Amy Parkinson Nottingham Trent University School of Science and Technology New Hall Block 178 Clifton Nottingham NG11 8NS Email: amy.parkinson@ntu.ac.uk	Dr Charlotte Apps Nottingham Trent University School of Science and Technology New Hall Block 168 Clifton Nottingham NG11 8NS Telephone: 01158 484831 Email: charlotte.apps@ntu.ac.uk

A2.3. Participant Statement of Consent for Data Collection 1

Study title: Strength Asymmetry in Athletes (SAAS - Longitudinal Testing)

1. I, ... agree to partake as a participant in the above study.
2. I understand from the participant information sheet (Dated… Version…), which I have read in full, and from my discussion(s) with .... that this will involve me attending the lab for data collection on four occasions; one session will last approximately 2.5hrs and the remaining three will last approximately 1hr.
3. It has also been explained to me by .... that the risks and side effects that may result from my participation are as follows: fatigue as well as breathlessness post effort and possible muscle soreness in the days that follow.
4. I confirm that I have had the opportunity to ask questions about the study and, where I have asked questions, these have been answered to my satisfaction.
5. I undertake to abide by University regulations and the advice of researchers regarding safety.
6. I am aware that I can withdraw my consent to participate in the procedure at any time and for any reason, without having to explain my withdrawal and that my personal data will be destroyed and that my medical care or legal rights will not be affected.
7. I understand that any personal information regarding me, gained through my participation in this study, will be treated as confidential and only handled by individuals relevant to the performance of the study and the storing of information thereafter. Where information concerning myself appears within published material, my identity will be kept anonymous.
8. I confirm that I have had the University's policy relating to the storage and subsequent destruction of sensitive information explained to me. I understand that sensitive information I have provided through my participation in this study, in the form of anthropometric, 3D scans, strength, training and injury data will be handled in accordance with this policy.
9. I confirm that I have completed the health questionnaire and know of no reason, medical or otherwise that would prevent me from partaking in this research.
10. I understand that the information collected about me will be used to support other research in the future and may be shared anonymously with other researchers.
11. I understand that a feedback report based on my data will be provided to myself and my NTU coaching team which may be used for training and injury prevention strategies.
12. I confirm that I am aware that I need to complete a COVID19 symptom questionnaire prior to every trial in the study / visit to the University's research facilities.
13. I confirm that I recognise that my involvement with this research could result in an increased risk of me contracting COVID19, despite all the mitigation employed by the researchers.

Participant signature: ____________________________ Date: ________

Independent witness signature: __________________________ Date: ________

Primary Researcher signature: __________________________ Date: ________

A2.4. Participant Statement of Consent for Data Collection 2

Study title: Strength Asymmetry in Athletes (SAAS - Preseason Testing)

1. I, ... agree to partake as a participant in the above study.
2. I understand from the participant information sheet (Dated… Version…), which I have read in full, and from my discussion(s) with .... that this will involve me attending the lab for data collection on three occasions; two sessions will last approximately 1hr and one will last approximately 2hrs.
3. It has also been explained to me by .... that the risks and side effects that may result from my participation are as follows: fatigue as well as breathlessness post effort and possible muscle soreness in the days that follow.
4. I confirm that I have had the opportunity to ask questions about the study and, where I have asked questions, these have been answered to my satisfaction.
5. I undertake to abide by University regulations and the advice of researchers regarding safety.
6. I am aware that I can withdraw my consent to participate in the procedure at any time and for any reason, without having to explain my withdrawal and that my personal data will be destroyed and that my medical care or legal rights will not be affected.
7. I understand that any personal information regarding me, gained through my participation in this study, will be treated as confidential and only handled by individuals relevant to the performance of the study and the storing of information thereafter. Where information concerning myself appears within published material, my identity will be kept anonymous.
8. I confirm that I have had the University's policy relating to the storage and subsequent destruction of sensitive information explained to me. I understand that sensitive information I have provided through my participation in this study, in the form of anthropometric, 3D scans, strength, training and injury data will be handled in accordance with this policy.
9. I confirm that I have completed the health questionnaire and know of no reason, medical or otherwise that would prevent me from partaking in this research.
10. I understand that the information collected about me will be used to support other research in the future and may be shared anonymously with other researchers.
11. I understand that a feedback report based on my data will be provided to myself and my NTU coaching team which may be used for training and injury prevention strategies.
12. I confirm that I am aware that I need to complete a COVID19 symptom questionnaire prior to every trial in the study / visit to the University's research facilities.
13. I confirm that I recognise that my involvement with this research could result in an increased risk of me contracting COVID19, despite all the mitigation employed by the researchers.

Participant signature: ______________________ Date: ________

Independent witness signature: ______________________ Date: ________

Primary Researcher signature: ______________________ Date: ________

A2.5. Participant Health Scree For Data Collection 1 and 2

Name or Number ....

Please complete this brief questionnaire to confirm fitness to participate:

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

(a)	on medication, prescribed or otherwise	Yes ☐	No ☐
(b)	attending your general practitioner	Yes ☐	No ☐
(c)	on a hospital waiting list	Yes ☐	No ☐

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

(a)	consult your GP	Yes ☐	No ☐
(b)	attend a hospital outpatient department	Yes ☐	No ☐
(c)	be admitted to hospital	Yes ☐	No ☐

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

(a)	Convulsions/epilepsy	Yes ☐	No ☐
(b)	Asthma	Yes ☐	No ☐
(c)	Eczema	Yes ☐	No ☐
(d)	Diabetes	Yes ☐	No ☐
(e)	A blood disorder	Yes ☐	No ☐
(f)	Head injury	Yes ☐	No ☐
(g)	Digestive problems	Yes ☐	No ☐
(h)	Heart problems	Yes ☐	No ☐
(i)	Problems with bones or joints	Yes ☐	No ☐
(j)	Disturbance of balance / coordination	Yes ☐	No ☐
(k)	Numbness in hands or feet	Yes ☐	No ☐
(l)	Disturbance of vision	Yes ☐	No ☐
(m)	Ear / hearing problems	Yes ☐	No ☐
(n)	Thyroid problems	Yes ☐	No ☐
(o)	Kidney or liver problems	Yes ☐	No ☐
(p)	Allergy to nuts, alcohol etc.	Yes ☐	No ☐
(q)	Any problems affecting your nose e.g. recurrent nose bleeds	Yes ☐	No ☐

(r) Any nasal fracture or deviated nasal septum Yes ☐ No ☐

4. **Has any,** otherwise healthy, member of your family under the age of 50 died suddenly during or soon after exercise? Yes ☐ No ☐

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

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

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

8. Have you ever tested positive for COVID Yes ☐ No ☐

<u>**Women only**</u>

9. Are you pregnant, trying to become pregnant or breastfeeding?Yes ☐ No ☐

If YES to any question, please describe briefly if you wish (e.g. to confirm problem was/is short-lived, insignificant or well controlled.) ....

....…

….……………………...………………………………………………………………

………………………………………..

Appendix 3. Training and Injury Reporting

A3.1. Athlete Training Report Form

This form is to be completed by one coach from each sports team during periods of testing for the 'Strength Asymmetry in Athletes (SAAS)' study at the start and end of preseason and the competition phase. The following questions refer to the training being delivered by NTU Sport at the time of completion.

Full Name: ___________________________
Sport: _________________________
Form completion date: _____________________________

1. **What is the main purpose of training at this timepoint in the season?** (please select one)

☐ Improve aspects of physical fitness (cardiovascular endurance, muscular strength, muscular endurance, flexibility, body composition)

☐ Improve sports-specific performance (sport-specific tasks, drills, set plays, match play)

☐ Reduce injury risk

☐ Other, please specify ______________________________

2. **How many times a week does your team train as part of NTU Sport?**

____

3. **How long does a typical training session last?** (please select one)

☐ ⩽ 30 mins

☐ 30-45 mins

☐ 45-60mins

☐ 60-90mins

☐ ⩾ 90mins

4. **How often does your team compete for NTU?** (please select one)

☐ Not currently competing

☐ Once a week

☐ More than once a week

5. **How long does a typical game last?**

____

Please return to amy.parkinson@ntu.ac.uk

A3.2. Athlete Injury Report Form

This form should be completed by the athlete following an injury that 1) is likely to affect their participation in the 'Strength Asymmetry in Athletes' study and 2) results in the restriction of the athlete's sport participation for 1 or more days beyond the day of injury.

Athlete Name: ______________________________
Sport: _________________________
Coach's Name: _____________________________
Form completion date: ____________________________

1. **When did the injury occur?** ______________________________

2. **What area of the body was injured?** _____________________________

3. **How did the injury occur?** (please provide detail about the playing situation, athlete/opponent behaviour and movement that resulted in the injury)

____

____

4. What type of injury was sustained? (please select one)

☐ Ligament/joint sprain

☐ Muscle/tendon strain/tear

☐ Dislocation

☐ Fracture

☐ Other, please specify below

5. What treatment was prescribed (if any)?

____

____

6. How long do you expect your participation in training/matches to be affected? (please select one)

☐ None

☐ ⩽1 week

☐ 1-2 weeks

☐ 3-4 weeks

☐ >4 weeks

☐ Out for the season

Please return to amy.parkinson@ntu.ac.uk

Appendix 4. Measurement Combinations and Parameter Error

A4.1. Knee Flexion

Table A4.1 Best and worst three combinations and associated parameter errors (%) using three, five, seven and ten measurement angles (in degrees) to predict knee flexion torque-angle characteristics

Parameter		3 Measurement Angles		5 Measurement Angles		7 Measurement Angles		10 MeasurementAngles (Max)	
		Combination	Error	Combination	Error	Combination	Error	Combination	Error
T_0	Best	100,170,180*	3.1	100,130,150,160,180*	3.5	110,120,130,140,160,170,180	3.8	ALL	4.7
		120,170,180*	3.3	120,130,150,170,180*	3.6	90,110,120,140,150,170,180	3.9		
		110,170,180*	3.3	90,100,110,170,180*	3.7	90,110,140,150,160,170,180	3.9		
	Worst	90,110,130	13.7	90,100,110,120,130	13.3	90,100,110,120,130,140,150	9.0		
		90,100,130	13.5	90,100,120,130,140	13.1	90,100,110,120,140,150,160	7.1		
		90,120,130	13.5	90,100,110,120,140	12.6	100,110,120,130,140,150,160	7.1		
θ_{opt}	Best	100,130,180*	4.8	90,120,140,150,180*	3.1	90,100,120,130,140,150,180*	3.3	ALL	4.6
		90,150,180*	5.4	90,110,120,140,180*	3.5	90,100,130,140,150,170,180*	3.4		
		100,150,180*	5.6	90,100,130,140,180*	3.5	90,110,120,130,140,170,180*	3.5		
	Worst	90,100,150	16.0	90,100,120,130,140	9.9	90,100,110,120,130,140,150	7.7		
		90,100,160	15.5	90,100,110,120,130	9.7	100,110,120,130,140,150,160	7.2		
		90,100,160	14.7	110,120,130,140,150	9.7	90,100,110,120,140,150,160	6.8		
k_2	Best	100,130,180*	18.4	90,100,130,140,180*	15.2	90,100,120,130,140,150,180*	14.2	ALL	17.5
		100,150,180*	21.1	90,100,130,160,180*	15.7	90,100,130,140,150,170,180*	14.3		
		100,140,180*	22.1	90,100,120,140,180*	15.7	90,100,120,140,150,170,180*	14.7		
	Worst	90,110,160	224.7	90,120,130,140,150	80.7	90,100,110,120,130,140,150	38.0		
		90,100,150	221.6	90,140,150,160,170	75.0	90,110,120,130,140,150,160	36.1		
		90,100,160	188.6	110,120,130,140,150	62.5	90,120,130,140,150,160,170	34.8		

T_0 = peak isometric torque (Nm); θ_{opt} = optimal angle (°); k_2 = width; * indicates measurement angle closest to the optimal angle

A4.2. Knee Extension

Table A4.2 Best and worst three combinations and associated parameter errors (%) using three, five, seven and nine measurement angles (in degrees) to predict knee extension torque-angle characteristics

Parameter		3 Measurement Angles		5 Measurement Angles		7 Measurement Angles		9 Measurement Angles (Max)	
		Combination	**Error**	**Combination**	**Error**	**Combination**	**Error**	**Combination**	**Error**
$\boldsymbol{T_0}$	**Best**	200,240*,250	2.3	200,220,230,240*,270	2.2	200,220,230,240*,250,260,280	2.5	ALL	2.9
		210,230,250	2.5	200,210,240*,250,260	2.5	200,210,220,230,240*,250,260	2.7		
		230,240*,280	2.5	200,230,240*,250,260	2.5	200,210,230,240*,250,260,270	2.7		
	Worst	260,270,280	9.6	200,210,250,260,270	4.6	200,210,220,240*,250,270,280	3.6		
		200,210,220	9.2	200,210,260,270,280	4.5	200,210,220,240*,260,270,280	3.4		
		210,220,230	8.4	200,210,220,270,280	4.5	210,220,230,250,260,270,280	3.3		
$\boldsymbol{\theta_{opt}}$	**Best**	210,230,280	0.1	200,220,250,270,280	0.1	200,210,230,240*,260,270,280	0.1	ALL	0.1
		210,250,280	0.1	200,210,240*,270,280	0.1	200,210,220,240*,260,270,280	0.1		
		200,240*,280	0.1	200,230,240*,270,280	0.1	200,210,220,230,260,270,280	0.1		
	Worst	240*,250,260	6.2	240*,250,260,270,280	1.5	200,210,220,230,240*,250,260	0.2		
		220,230,240*	4.9	200,210,220,230,240*	1.4	220,230,240*,250,260,270,280	0.2		
		250,260,270	4.4	210,220,230,240*,250	0.7	200,210,220,240*,250,260,270	0.1		
$\boldsymbol{k_2}$	**Best**	200,230,280	2.4	200,240*,260,270,280	2.2	200,220,230,240*,250,270,280	2.3	ALL	3.3
		200,240*,280	2.6	200,220,230,250,280	2.2	200,210,220,240*,260,270,280	2.3		
		200,250,280	2.6	200,220,230,240*,280	2.3	200,210,230,240*,260,270,280	2.3		
	Worst	240*,250,260	47.1	240*,250,260,270,280	14.1	220,230,240*,250,260,270,280	4.5		
		220,230,240*	41.4	200,210,220,230,240*	12.4	210,220,230,240*,250,260,270	4.2		
		230,240*,250	34.9	210,220,230,240*,250	10.4	200,210,220,230,240*,250,260	4.0		

T_0 = peak isometric torque (Nm); θ_{opt} = optimal angle (°); k_2 = width; * indicates measurement angle closest to the optimal angle

Appendix 5. Supplementary Results for Longitudinal Testing

A5.1. Reliability Statistics

Table A5.1 Within-session reliability data for bilateral and unilateral jumping in male (*n* = 21) and female (*n* = 17) athletes at four timepoints throughout the season, using the coefficient of variation (CV) and intraclass correlation coefficient (ICC) with 95% confidence intervals (CI)

	Countermovement Jump				Horizontal Jump			
	Males		Females		Males		Females	
	CV (%)	ICC (95% CI)	CV (%)	ICC (95% CI)	CV (%)	ICC (95% CI)	CV (%)	ICC (95% CI)
Bilateral								
Preseason 1	1.5	0.99 (0.90-1.00)	3.6	0.99 (0.90-1.00)	2.0	0.97 (0.59-0.99)	2.0	0.97 (0.27-0.99)
Preseason 2	2.1	0.99 (0.79-1.00)	2.0	0.97 (0.61-0.99)	2.4	0.96 (0.70-0.99)	1.8	0.96 (0.52-0.99)
Competition 1	2.1	0.99 (0.60-1.00)	3.1	0.94 (0.41-0.98)	1.0	0.99 (0.91-1.00)	1.3	0.97 (0.60-0.99)
Competition 2	1.6	0.99 (0.95-1.00)	2.2	0.99 (0.79-1.00)	1.3	0.99 (0.77-1.00)	1.4	0.97 (0.62-0.99)
Unilateral: R								
Preseason 1	5.2	0.91 (0.50-0.97)	6.0	0.94 (0.41-0.98)	3.1	0.94 (0.50-0.99)	3.0	0.96 (0.28-0.99)
Preseason 2	5.1	0.94 (0.51-0.98)	3.8	0.96 (0.34-0.99)	1.9	0.98 (0.69-0.99)	2.0	0.97 (0.54-0.99)
Competition 1	5.2	0.94 (0.3-0.99)	6.1	0.88 (-0.12-0.97)	1.5	0.98 (0.68-1.00)	1.4	0.98 (0.80-1.00)
Competition 2	3.3	0.98 (0.51-0.99)	5.1	0.95 (0.62-0.99)	1.8	0.98 (0.79-0.99)	1.2	0.98 (0.86-0.99)
Unilateral: L								
Preseason 1	4.9	0.97 (0.51-0.99)	3.5	0.98 (0.84-0.99)	2.1	0.99 (0.84-1.00)	2.8	0.95 (0.45-0.99)
Preseason 2	3.8	0.97 (0.82-0.99)	6.5	0.84 (0.34-0.95)	2.7	0.96 (0.50-0.99)	2.6	0.97 (0.10-0.99)
Competition 1	3.9	0.98 (0.66-0.99)	3.5	0.94 (0.42-0.99)	1.4	0.98 (0.71-1.00)	1.3	0.98 (0.61-1.00)
Competition 2	4.4	0.97 (0.54-0.99)	4.8	0.94 (0.70-0.98)	1.3	0.99 (0.57-1.00)	1.2	0.99 (0.76-1.00)

R = right limb, L = left limb

Table A5.2 Within-session reliability data for bilateral and unilateral jumping in basketball (*n* = 12), hockey (*n* = 16) and netball (*n* = 10) athletes at four timepoints throughout the season, using the coefficient of variation (CV) and intraclass correlation coefficient (ICC) with 95% confidence intervals (CI)

Test/ Timepoint	**Countermovement Jump**						**Horizontal Jump**					
	Basketball		**Hockey**		**Netball**		**Basketball**		**Hockey**		**Netball**	
	CV (%)	ICC (95% CI)	CV (%)	ICC (95% CI)	CV (%)	ICC (95% CI)	CV (%)	ICC (95% CI)	CV (%)	ICC (95% CI)	CV (%)	ICC (95% CI)
Bilateral												
Preseason 1	2.3	0.99 (0.84-1.00)	1.8	0.99 (0.93-1.00)	3.6	0.93 (0.46-0.99)	1.8	0.98 (0.77-1.00)	2.1	0.98 (0.31-1.00)	2.1	0.96 (0.19-0.99)
Preseason 2	2.1	0.99 (0.84-1.00)	1.9	0.99 (0.85-1.00)	2.1	0.95 (0.30-0.99)	3.2	0.96 (0.57-0.99)	1.7	0.99 (0.79-1.00)	1.7	0.95 (0.37-0.99)
Competition 1	2.5	0.99 (0.60-1.00)	2.1	0.99 (0.78-1.00)	3.3	0.92 (0.34-0.98)	0.9	0.99 (0.95-1.00)	1.1	0.99 (0.76-1.00)	1.6	0.97 (0.45-0.99)
Competition 2	1.7	0.99 (0.95-1.00)	2.1	0.99 (0.95-1.00)	1.7	0.98 (0.62-1.00)	1.3	0.99 (0.83-1.00)	1.4	0.99 (0.69-1.00)	1.2	0.98 (0.80-1.00)
Unilateral: R												
Preseason 1	6.6	0.92 (0.51-0.98)	5.1	0.96 (0.58-1.00)	4.9	0.96 (0.35-0.99)	2.7	0.97 (0.73-0.99)	3.4	0.94 (0.31-0.99)	2.9	0.97 (0.23-0.99)
Preseason 2	4.4	0.96 (0.66-0.99)	5.3	0.96 (0.18-0.99)	3.6	0.97 (0.74-0.99)	1.9	0.98 (0.77-1.00)	2.0	0.98 (0.55-1.00)	1.9	0.97 (0.68-0.99)
Competition 1	6.0	0.94 (0.11-1.00)	4.8	0.95 (0.25-1.00)	6.3	0.86 (-0.15-0.97)	1.4	0.99 (0.80-1.00)	1.8	0.99 (0.70-1.00)	1.1	0.99 (0.91-1.00)
Competition 2	5.2	0.95 (0.44-0.99)	3.7	0.99 (0.91-1.00)	3.4	0.96 (0.13-0.99)	1.6	0.99 (0.91-1.00)	1.6	0.98 (0.82-0.99)	1.4	0.98 (0.71-1.00)
Unilateral: L												
Preseason 1	4.3	0.98 (0.78-1.00)	4.3	0.98 (0.79-1.00)	4.3	0.96 (0.47-0.99)	2.3	0.99 (0.89-1.00)	1.7	0.99 (0.83-1.00)	3.6	0.93 (0.05-0.99)
Preseason 2	3.1	0.98 (0.88-1.00)	5.9	0.92 (0.70-0.97)	5.8	0.71 (-0.21-0.93)	2.8	0.98 (0.40-1.00)	2.5	0.97 (0.61-0.99)	2.6	0.97 (0.12-1.00)
Competition 1	4.3	0.98 (0.54-1.00)	4.2	0.96 (0.68-0.99)	2.3	0.70 (0.39-1.00)	1.3	0.99 (0.85-1.00)	1.2	0.99 (0.88-1.00)	1.6	0.98 (0.26-1.00)
Competition 2	3.6	0.99 (0.90-1.00)	4.6	0.98 (0.70-0.99)	5.6	0.87 (0.19-0.97)	1.2	1.00 (0.86-1.00)	1.4	0.99 (0.55-1.00)	1.2	0.97 (0.62-0.99)

R = right limb, L = left limb

A5.2. Effect Sizes

Table A5.3 Within-subject effect sizes (g and 95% confidence intervals) for performance and inter-limb asymmetry during bilateral and unilateral jumping in male (n = 21) and female (n = 17) athletes across the season

Test/Timepoint	**Countermovement Jump**		**Horizontal Jump**	
	Males	**Females**	**Males**	**Females**
Bilateral				
Pre1 to Pre2	-0.12 (-0.29- to 0.05)	0.21 (-0.16 to 0.59)	0.25 (-0.02 to 0.55)	0.01 (-0.24 to 0.25)
Pre1 to Comp1	-0.18 (-0.37 to 0.00)	0.45 (0.01 to 0.93)	0.40 (0.11 to 0.73)	0.42 (0.00 to 0.87)
Pre1 to Comp2	-0.01 (-0.23 to 0.20)	0.29 (-0.17 to 0.78)	0.45 (0.16 to 0.76)	0.35 (-0.05 to 0.77)
Pre2 to Comp1	-0.06 (-0.22 to 0.10)	0.29 (0.01 to 0.61)	0.13 (-0.07 to 0.34)	0.42 (0.07 to 0.81)
Pre2 to Comp2	0.10 (-0.11 to 0.31)	0.13 (-0.17 to 0.45)	0.17 (-0.06 to 0.42)	0.35 (-0.02 to 0.74)
Comp1 to Comp2	0.15 (-0.06 to 0.38)	-0.11 (-0.42 to 0.18)	0.05 (-0.15 to 0.26)	-0.07 (-0.33 to 0.17)
Unilateral: R				
Pre1 to Pre2	-0.11 (-0.46 to 0.23)	0.10 (-0.20 to 0.41)	0.16 (-0.11 to 0.44)	0.36 (-0.14 to 0.89)
Pre1 to Comp1	-0.02 (-0.35 to 0.29)	0.47 (0.09 to 0.90)	0.68 (0.34 to 1.09)	0.42 (-0.04 to 0.91)
Pre1 to Comp2	0.06 (-0.23 to 0.34)	0.01 (-0.42 to 0.44)	0.39 (0.04 to 0.78)	0.42 (-0.08 to 0.96)
Pre2 to Comp1	0.08 (-0.15 to 0.31)	0.41 (0.06 to 0.80)	0.51 (-0.26 to 0.80)	0.07 (-0.35 to 0.51)
Pre2 to Comp2	0.16 (-0.12 to 0.45)	-0.08 (-0.52 to 0.35)	0.23 (-0.01 to 0.49)	0.06 (-0.42 to 0.54)
Comp1 to Comp2	0.07 (-0.21 to 0.36)	-0.44 (-0.80 to -0.11)	-0.28 (-0.55 to -0.03)	-0.02 (-0.41 to 0.37)
Unilateral: L				
Pre1 to Pre2	0.11 (-0.16 to 0.39)	0.03 (-0.32 to 0.39)	0.27 (-0.11 to 0.66)	0.02 (-0.36 to 0.41)
Pre1 to Comp1	0.00 (-0.25 to 0.25)	0.27 (-0.12 to 0.69)	0.56 (0.02 to 1.14)	0.59 (0.02 to 1.23)
Pre1 to Comp2	0.16 (-0.07 to 0.40)	0.08 (-0.44 to 0.60)	0.35 (-0.04 to 0.76)	0.48 (-0.10 to 1.11)
Pre2 to Comp1	-0.12 (-0.37 to 0.12)	0.30 (-0.09 to 0.71)	0.41 (0.11 to 0.74)	0.54 (0.16 to 0.97)
Pre2 to Comp2	0.06 (-0.22 to 0.34)	0.05 (-0.33 to 0.44)	0.10 (-0.17 to 0.39)	0.44 (-0.02 to 0.94)
Comp1 to Comp2	0.17 (-0.02 to 0.37)	-0.23 (-0.61 to 0.13)	-0.33 (-0.68 to -0.01)	-0.10 (-0.58 to 0.38)

Table A5.3 Within-subject effect sizes (*g* and 95% confidence intervals) for performance and inter-limb asymmetry during bilateral and unilateral jumping in male (*n* = 21) and female (*n* = 17) athletes across the season (*continued)*

Test/Timepoint	**Countermovement Jump**		**Horizontal Jump**	
	Males	**Females**	**Males**	**Females**
Unilateral: ASI				
Pre1 to Pre2	-0.41 (-1.04 to 0.20)	-0.15 (-0.85 to 0.54)	-0.41 (-1.04 to 0.20)	0.00 (-0.60 to 0.60)
Pre1 to Comp1	-0.23 (-0.82 to 0.34)	-0.49 (-1.19 to 0.16)	-0.63 (-1.36 to 0.05)	-0.55 (-1.29 to 0.14)
Pre1 to Comp2	-0.13 (-0.57 to 0.29)	-0.30 (-1.06 to 0.43)	-0.30 (-0.87 to 0.25)	-0.28 (-0.97 to 0.38)
Pre2 to Comp1	0.19 (-0.47 to 0.85)	-0.32 (-1.15 to 0.49)	-0.28 (-1.01 to 0.42)	-0.48 (-1.22 to 0.21)
Pre2 to Comp2	0.29 (-0.29 to 0.90)	-0.17 (-1.05 to 0.70)	0.14 (-0.47 to 0.75)	-0.24 (-1.10 to 0.50)
Comp1 to Comp2	0.11 (-0.43 to 0.65)	0.11 (-0.53 to 0.76)	0.42 (-0.26 to 1.14)	0.26 (-0.46 to 1.00)

R = right limb; L = left limb, ASI = asymmetry index

Table A5.4 Within-subject effect sizes (*g* and 95% confidence intervals) for performance and inter-limb asymmetry during bilateral and unilateral jumping in basketball (*n* = 12), hockey (*n* = 16) and netball (*n* = 10) athletes across the season

Test/Timepoint	Countermovement Jump			Horizontal Jump		
	Basketball	**Hockey**	**Netball**	**Basketball**	**Hockey**	**Netball**
Bilateral						
Pre1 to Pre2	-0.04 (-0.23 to 0.14)	-0.04 (-0.30 to 0.22)	0.22 (-0.26 to 0.75)	0.00 (-0.23 to 0.23)	0.24 (-0.07 to 0.58)	0.20 (-0.11 to 0.54)
Pre1 to Comp1	-0.14 (-0.40 to 0.10)	0.02 (-0.24 to 0.28)	0.52 (-0.09 to 1.24)	0.25 (-0.01 to 0.54)	0.41 (0.03 to 0.83)	0.52 (-0.19 to 1.32)
Pre1 to Comp2	-0.04 (-0.29 to 0.21)	0.05 (-0.28 to 0.17)	0.77 (0.02 to 1.68)	0.19 (-0.14 to 0.56)	0.44 (0.13 to 0.79)	0.51 (-0.13 to 1.24)
Pre2 to Comp1	-0.09 (-0.31 to 0.12)	0.06 (-0.11 to 0.23)	0.41 (0.04 to 0.86)	0.22 (0.03 to 0.44)	0.12 (-0.11 to 0.36)	0.37 (-0.18 to 0.98)
Pre2 to Comp2	0.00 (-0.25 to 0.26)	-0.02 (-0.18 to 0.13)	0.73 (0.21 to 1.40)	0.18 (-0.08 to 0.46)	0.15 (-0.11 to 0.43)	0.36 (-0.13 to 0.92)
Comp1 to Comp2	0.10 (-0.22 to 0.43)	-0.07 (-0.24 to 0.09)	0.27 (-0.13 to 0.72)	-0.04 (-0.32 to 0.24)	0.04 (-0.16 to 0.25)	0.01 (-0.15 to 0.17)
Unilateral: R						
Pre1 to Pre2	-0.07 (-0.41 to 0.26)	0.01 (-0.31 to 0.32)	0.05 (-0.47 to 0.59)	0.24 (-0.10 to 0.62)	0.02 (-0.24 to 0.28)	0.50 (-0.27 to 1.35)
Pre1 to Comp1	0.10 (-0.26 to 0.48)	0.05 (-0.29 to 0.40)	0.51 (-0.11 to 1.22)	0.61 (0.15 to 1.17)	0.33 (0.07 to 0.61)	0.54 (-0.15 to 1.34)
Pre1 to Comp2	0.10 (-0.23 to 0.44)	-0.13 (-0.42 to 0.15)	0.31 (-0.35 to 1.03)	0.57 (0.06 to 1.17)	0.33 (0.00 to 0.69)	0.39 (-0.35 to 1.21)
Pre2 to Comp1	0.17 (-0.14 to 0.51)	0.05 (-0.21 to 0.32)	0.52 (0.02 to 1.12)	0.38)0.09 to 0.73)	0.31 (0.06 to 0.60)	0.06 (-0.62 to 0.75)
Pre2 to Comp2	0.14 (-0.08 to 0.38)	-0.14 (-0.51 to 0.22)	0.29 (-0.24 to 0.88)	0.13 (-0.19 to 0.48)	0.32 (0.07 to 0.59)	-0.16 (-0.88 to 0.53)
Comp1 to Comp2	-0.03 (-0.34 to 0.27)	-0.18 (-0.50 to 0.11)	-0.18 (-0.73 to 0.32)	-0.23 (-0.62 to 0.13)	-0.03 (-0.30 to 0.24)	-0.22 (-0.56 to 0.07)
Unilateral: L						
Pre1 to Pre2	0.13 (-0.26 to 0.53)	0.01 (-0.19 to 0.22)	0.08 (-0.42 to 0.60)	0.32 (-0.20 to 0.90)	0.06 (-0.20 to 0.33)	-0.04 (-0.53 to 0.45)
Pre1 to Comp1	0.03 (-0.28 to 0.34)	0.06 (-0.24 to 0.38)	0.28 (-0.33 to 0.93)	0.53 (-0.22 to 1.37)	0.42 (0.11 to 0.78)	0.54 (-0.25 to 1.44)
Pre1 to Comp2	-0.05 (-0.36 to 0.26)	0.08 (-0.20 to 0.36)	0.44 (-0.38 to 1.33)	0.34 (-0.22 to 0.96)	0.30 (-0.05 to 0.67)	0.49 (-0.33 to 1.40)
Pre2 to Comp1	-0.10 (-0.45 to 0.23)	0.05 (-0.26 to 0.38)	0.33 (-0.08 to 0.80)	0.26 (-0.12 to 0.67)	0.37 (0.10 to 0.69)	0.57 (0.07 to 1.17)
Pre2 to Comp2	-0.17 (-0.49 to 0.12)	0.07 (-0.20 to 0.35)	0.61 (-0.02 to 1.37)	0.02 (-0.31 to 0.34)	0.24 (-0.12 to 0.63)	0.52 (0.01 to 1.12)
Comp1 to Comp2	-0.08 (-0.30 to 0.12)	0.02 (-0.26 to 0.31)	0.21 (-0.16 to 0.61)	-0.26 (-0.72 to 0.17)	-0.15 (-0.49 to -0.18)	-0.13 (-0.52 to 0.24)

Table A5.4 Within-subject effect sizes (*g* and 95% confidence intervals) for performance and inter-limb asymmetry during bilateral and unilateral jumping in basketball (*n* = 12), hockey (*n* = 16) and netball (*n* = 10) athletes across the season (*continued)*

Test/Timepoint	Countermovement Jump			Horizontal Jump		
	Basketball	**Hockey**	**Netball**	**Basketball**	**Hockey**	**Netball**
Unilateral: ASI						
Pre1 to Pre2	-0.23 (-0.96 to 0.46)	-0.50 (-1.39 to 0.34)	-0.04 (-0.85 to 0.77)	-0.48 (-1.16 to 0.13)	-0.20 (-1.01 to 0.59)	0.18 (-0.71 to 1.10)
Pre1 to Comp1	0.00 (-0.91 to 0.91)	-0.50 (-1.17 to 0.12)	-0.50 (-1.47 to 0.38)	-0.50 (-1.58 to 0.49)	-0.40 (-1.16 to 0.32)	-0.96 (-2.06 to -0.04)
Pre1 to Comp2	0.04 (-0.70 to 0.78)	0.01 (-0.39 to 0.42)	-0.91 (2.28 to 0.29)	-0.17 (-0.77 to 0.40)	-0.07 (-0.80 to 0.65)	-0.76 (-1.96 to 0.28)
Pre2 to Comp1	0.26 (-0.74 to 1.30)	0.06 (-0.72 to 0.84)	-0.46 (-1.71 to 0.69)	-0.03 (-1.00 to 0.94)	-0.17 (-0.89 to 0.53)	-1.00 (-2.19 to 0.01)
Pre2 to Comp2	0.26 (-0.46 to 1.01)	0.53 (-0.31 to 1.42)	-0.87 (-2.22 to 0.32)	0.43 (-0.19 to 1.12)	0.15 (-0.72 to 1.03)	-0.82 (-1.90 to 0.10)
Comp1 to Comp2	0.04 (-0.70 to 0.78)	0.53 (-0.20 to 1.32)	-0.33 (-1.21 to 0.50)	0.47 (-0.43 to 1.43)	0.36 (-0.42 to 1.18)	0.18 (-0.98 to 1.39)

R = right limb; L = left limb, ASI = asymmetry index