The use of an isometric squat test as a measure of lower body maximal strength

Item Type	Thesis
Authors	Lynch, Arthur
Download date	2026-04-16 01:56:08
Item License	https://creativecommons.org/licenses/by-nc-sa/1.0/
Link to Item	https://hdl.handle.net/10344/10365

The use of an isometric squat test as a measure of lower body maximal strength

Arthur Lynch

A thesis submitted to the University of Limerick in candidacy for the degree of Doctor of Philosophy

Supervisors

Dr. Brian Carson, Dr. Robert Davies and Dr. Joanna Allardyce

Submitted to the University of Limerick

8th September 2020

The use of an isometric squat test as a measure of lower body maximal strength

Arthur Lynch
University of Limerick

Abstract

A number of different tests can be utilised for the measurement of lower body maximal strength. The isometric squat (ISq) is a highly controlled and externally valid test of lower body maximal strength. This research aimed to add to the knowledge base of the overall usefulness of the ISq as a measure of lower body maximal strength. The first experimental study established the reliability of the test at a 120°, 90° and 65° knee angle position; the latter placed subjects in a previously unexplored deep squat position. All positions demonstrated acceptable reliability (≤ 10 % CV, ≥ 0.8 ICC) for maximal (peak isometric force) but not explosive (rate of force development) strength. The characteristics of the ISq suggest it is appropriate to use regardless of an individual's maximal strength level. This hypothesis was tested by comparing the reliability of the ISq across a heterogeneous sample, covering the entire strength spectrum from untrained individuals to highly trained strength athletes. Similar reliability was evident across the entire sample, with no relationship between ISq strength and reliability. In order to determine the sensitivity of the ISq to measure changes in strength as an outcome, maximal strength changes in response to 6 weeks of ecologically valid strength training were assessed in a group of moderately trained males. The ISq was sensitive to detect changes in maximal strength. Use of a dual force plate ISq apparatus allows for separate individual analysis of the lower limbs; facilitating the monitoring of inter-limb asymmetries. The use of the ISq to detect bilateral vs. unilateral training induced changes in inter-limb asymmetry was assessed in moderately trained males. Both forms of training were effective at reducing inter-limb asymmetries. This thesis documents the overall utility and versatility of the ISq in the context of lower body maximal strength measurement.

Declaration

The work within this thesis is my own, and was completed with the counsel of supervisors Dr. Brian Carson, Dr. Robert Davies and Dr. Joanna Allardyce.

This work has not been submitted to any other University, Institution of higher education, for any other academic qualification or award.

Arthur Lynch

Acknowledgements

I would like to acknowledge and thank the following people in light of their contribution to this PhD:

Undergraduate research students Tim Locke, Sorcha Holohan, Morgan Lewis, Adam Jacob, Brian Coady, Ethan Bevan, Cian Butler, Niall Mulcahy, Patrick Garvey and Jack Heavey for assisting in the conduct of the experimental work.

The Physical Education and Sport Science (PESS) department for their financial support from 2015-2019.

Elaine Moore, UL structured PhD administrator.

Rob Burke, Jay Farrant, Sean Ryan and the entire community of the Irish Powerlifting Federation for the lending of equipment and general support in the pursuit of my PhD.

Sinead Kelly, Sean O’Sullivan Thomas Faherty and Martina Meaney of UL Sport for the lending of equipment, help with recruitment of subjects and all the support they have given me over the years.

Danny Lennon of Sigma Nutrition.

Gar Benn of CityGym Limerick for his unwavering support and generosity.

Fellow coaches and members of the CityGym Limerick community.

My family, even though I know I won’t ever be able to repay you for all you’ve done, I still intend to give it my best shot!

My girlfriend Laura for all the help and patience you’ve shown throughout this process. Hopefully I won’t be a burden on you for too much longer!

Prof. Phil Jakeman for getting me into the PhD programme as well as the learning experiences and insights shared with me. I very much appreciate all you have done for me.

I would like to thank all the subjects for donating their time and effort to participate in the studies.

Finally, I would like to thank my supervisors Dr. Brian Carson, Dr. Robert Davies and Dr. Joanna Allardyce for the commitment and support they have given me over the course of this PhD project. A special mention to Dr. Brian Carson for sticking by me and believing I was capable of completing the PhD at a time when I felt that it would no longer be possible.

Table of Contents

List of Tables

List of Figures

List of Appendices

List of abbreviations

1RM	One repetition maximum
ANOVA	Analysis of variances
CI	Confidence intervals
CV	Coefficient of variation
ICC	Intraclass correlation coefficient
IMJT	Isometric multi-joint test
IMTP	Isometric mid-thigh pull
ISq	Isometric squat
ISq_{120}	Isometric squat performed at a 120° knee angle
ISq_{90}	Isometric squat performed at a 90° knee angle
ISq_{65}	Isometric squat performed at a 65° knee angle
MF	Maximum force
N	Newtons
$N \cdot kg^{-1}$	Newtons per kilogram of body mass
$N \cdot s^{-1}$	Newtons per second
PIF	Peak isometric force
RFD	Rate of force development
SI	Symmetry index

SD	Standard deviation
TE	Typical error

Chapter 1

1.0 Introduction

Muscular strength is defined as the ability to exert force under a given set of conditions, which include body position, the movement in which force is applied, contraction type and movement speed (Harman 1993). For the purpose of this thesis, the focus will centre on maximal strength, the upper limit of the ability to produce force (Taber *et al*. 2016), as distinct from explosive or reactive strength. Maximal strength (particularly measures of lower body maximal strength) has been shown to correlate highly with a number of indicators of sporting performance (Suchomel *et al*. 2016). These include sprint performance, measures of peak power output, jump performance and change of direction ability (Baker and Nance 1999; McBride *et al*. 2009; Nuzzo *et al*. 2008; Suchomel *et al*. 2016; Wisløff *et al*. 2004). Furthermore, increasing lower body maximal strength levels via strength training positively impacts performance in a wide variety of sporting domains (Bazyler *et al.* 2015; Keiner *et al*. 2014; Bolger *et al*. 2015; Speranza *et al*. 2016; Styles *et al*. 2016).

1.1 Criteria for effective performance assessment

Performance testing allows for the categorization of athletes, it can be used to monitor fatigue/readiness levels in athletes, provide quantitative data that can inform rehabilitation programs for injured athletes and ultimately can be used to indicate the effectiveness of training protocols (Taylor *et al*. 2012; Baltzopoulos and Brodie 1989; Abernethy *et al*. 1995). As such, it is important that the test used to assess the performance parameter of interest, in this case lower body maximal strength, satisfies the three criteria for a good performance test, as outlined by Currell and Jeukendrup (2008). These are:

1. Validity: relates to the degree to which the test measures what it intends to measure (Currell and Jeukendrup 2008). This comprises *logical/face validity* (whether a test measures what it is intended to measure when it is very difficult to truly assess), *criterion validity* (the extent to which the results of a test reflect and/or predict that of a criterion measure) and *construct validity* (the extent to which the test measures a performance level, e.g. can the test differentiate among differing levels of performance) (Currell and Jeukendrup 2008; Drake *et al*. 2017).

2. Reliability: refers to the reproducibility of the measure, or the extent to which the measurement produces the same value when repeated in the same subject or specimen under the same conditions (Lachin 2004). Reliability provides insight into the variation of a test protocol from both biological and technical sources (Currell and Jeukendrup 2008).

3. Sensitivity: indicates the ability of the test to detect changes over time (Currell and Jekendrup 2008) or more specifically the smallest change that a test can detect and be considered “real” (i.e. outside the error range of the measure). This can be quantified through a sensitivity index such as the minimum difference, the smallest worthwhile change, typical error associated with a test or a signal to noise ratio (whereby the signal is considered to be the change in performance as a result of an intervention and the noise is the within-subject CV (Weir 2005; Hopkins 2000; Currell and

Jeukendrup 2008). The potential merits of each approach are explored in greater detail in Chapter 3. As the smallest real change is dependent on the error associated with the measure, the sensitivity of a given test is dependent on its reliability. The sensitivity of a measure is of great relevance to athlete performance monitoring.

Additionally, within the discussion of selecting appropriate tests of performance, the following factors are also important to consider:

1. Internal validity: the amount of control exerted over potential confounding variables (Halperin *et al*. 2015).
2. External validity: the degree to which the results are applicable to other populations, settings or contexts (George *et al*. 2000).
3. Ecological validity: this specifically relates to whether the findings of a study can be generalized to naturalistic situations, such as clinical practice or in this case generally within the field of strength and conditioning (Andrade 2018).

1.2 Assessment of lower body maximal strength

Assessment of lower body maximal strength can provide valuable insight into one's physical condition, differentiate strength levels between individuals, highlight agonist-antagonist strength imbalances, deficits in strength between limbs (termed inter-limb asymmetries), as well as inform exercise load prescription for future training programs (Abernethy *et al*. 1995; Drid *et al*. 2009; Bazyler *et al*. 2014). As discussed in section 1.1, the quality of the data obtained from such an assessment is highly influenced by the test that is chosen. Broadly speaking, assessment of muscular strength can be conducted under isokinetic, isometric and/or isoinertial (isotonic) conditions, with each assessment mode offering its own unique advantages and limitations (Abernethy *et al*. 1995). These assessment modes will now be explored in detail in the following sections.

Isokinetic dynamometry

Isokinetic dynamometry allows for assessment of muscular force to be controlled by a pre-determined velocity and range of motion via an electromechanical device (Baltzopoulos and Brodie 1989). If more muscular force is applied to the dynamometer during the contraction, the resistance of the dynamometer increases in proportion to that of the muscular force in order to maintain the pre-set movement velocity. This allows for a constant angular velocity of movement, a confounding variable of isoinertial testing (e.g. one repetition maximum testing) and as such this is a highly reliable (CV ≤ 7 %, ICC ≥ 0.965) mode of assessment (Maffiuletti *et al*. 2007). However, critics of isokinetic dynamometry highlight how this mode of assessment bears little resemblance to the biomechanics of sporting actions by primarily utilising isolated, single joint assessment. Along similar lines, whilst the control of movement velocity may allow for greater internal validity, it could be argued that this comes at the expense of its external validity as assessment is typically isolated to a single joint action (e.g. unilateral knee extension), which is not representative of most performance-based contexts (Abernethy *et al*. 1995).

The logical/face validity of the test is dependent upon the context of its application. For monitoring inter-limb asymmetry of muscular force in an injured athlete, the test would appear to have a very high logical/face validity (Pua *et al*. 2008). Moreover, use of isokinetic dynamometry for the purpose of detecting inter-limb asymmetries has demonstrated the ability to predict subsequent injuries in some (Orchard *et al*. 1997; Croisier *et al*.

2008) but not all studies (Bennell *et al*. 1998). In the context of assessing the performance level of an uninjured athlete; the logical/face validity of isokinetic dynamometry would appear to be low.

As both isokinetic and isometric dynamometry testing procedures are typically conducted unilaterally (i.e. a separate assessment for each limb), this allows for assessment of inter-limb asymmetry in force production. Use of dynamometry in this application is quite prominent within the literature (Knapik *et al*. 1991; Croisier *et al*. 2008; Drid *et al*. 2009). However, data from Kuki *et al*. (2019) not only serve to highlight the specific nature of the inter-limb asymmetries, but also suggest that if bilateral performance (i.e. both limbs producing force simultaneously) is of interest to the investigator, then it may be worth considering performing a bilateral assessment of inter-limb asymmetry (if inter-limb asymmetry is deemed to be of relevance) as distinct from a unilateral assessment (such as conventional dynamometry) of inter-limb asymmetry. In a comparison of the bilateral and unilateral isometric mid-thigh pull (IMTP), significantly greater asymmetry scores were observed in the bilateral version of the IMTP compared to the unilateral IMTP (24 % vs. 10 % asymmetry respectively) (Kuki *et al*. 2019).

Isometric dynamometry

Isometric dynamometry typically utilises the same apparatus and single joint assessment as its isokinetic counterpart, but the assessment is performed under static conditions, whereby the muscle contracts with little or no change in length, allowing for maximum control of movement velocity and joint angle. Proponents of isometric dynamometry highlight the high level of control afforded with this type of assessment (Abernethy *et al*. 1995). In addition, isometric tests of strength are typically not prone to systematic bias, namely learning effects (Nuzzo *et al*. 2019). This means that they are also highly reliable, such as isolated isometric knee extension force (CV < 6 %, ICC > 0.9) (Maffiuletti *et al*. 2007). However, criticisms of isometric dynamometry largely revolve around the same concerns levelled at isokinetic dynamometry in that these tests bear little resemblance to the dynamic nature of most sporting tasks (Abernethy *et al*. 1995), meaning that for performance assessment in uninjured individuals the logical/face validity of this assessment is low.

Isoinertial assessments

In contrast with dynamometry, isoinertial lower body strength assessments involve the use of a fixed resistance (or a constant gravitational load) under dynamic conditions in a particular movement (usually a multi-joint, barbell based exercise) performed to a pre-determined range of motion. One repetition maximum (1RM) weightlifting tasks such as the 1RM back squat exercise are commonly used isoinertial assessments. The widespread availability of the equipment required to conduct these tests appeals to many practitioners and sport scientists alike. Another advantage of 1RM testing is the use of exercises that are regularly incorporated into typical strength training programs, which can then be used to inform future training load prescriptions. Compared to dynamometry, 1RM offers greater levels of external and ecological validity, with greater resemblance to the biomechanics of various sporting tasks; these include jumping, sprinting and scrummaging (MacKenzie *et al*. 2014; Choe *et al*. 2018; Mills *et al*. 2019), albeit at the expense of some internal validity. In addition, if the back squat is performed with the subject/athlete standing on two force plates, this also allows for the assessment of inter-limb asymmetry as the ground reaction forces produced at each limb can be measured and any deficits between limbs can be quantified (Hodges *et al*. 2011; Sato and Heise 2012; Kobayashi *et al*. 2012). In spite of this, to the best of the author’s knowledge no study has investigated the presence of inter-limb asymmetries in the 1RM back squat, nor has the relevance of inter-limb asymmetries in sub-maximal back squat tests to overall back squat performance been explored.

Methodological and practical considerations in the conduct of one repetition maximum back squat testing

Given the characteristics of the 1RM back squat (i.e. isoinertial multi-articular assessment, increased degrees of freedom relative to monoarticular assessment modes), this test can be confounded by changes in joint angle throughout the movement. During a 1RM assessment, the external load (i.e. the mass of the barbell) remains constant, whereas muscular tension varies throughout the movement. This is due to changes in joint angle (and the associated external moment arms created) and velocity during the movement, as well as the influence of barbell load on the relative muscular effort during the movement (Bryanton *et al*. 2012). The relative muscular effort of the knee and hip extensors increases as the range of motion during the back squat exercise increases, in particular once the range of motion moves beyond 90° of knee flexion (Bryanton *et al*. 2012). Furthermore, the 1RM back squat appears to be at least somewhat limited by the task-specific skill and strength-training experience of an individual (Nuzzo *et al*. 2019), with current evidence indicating that the 1RM back squat is not reliable in untrained populations (Ritti-Dias *et al*. 2011; Ribiero *et al*. 2014; Ryman Augustsson and Svantesson 2013).

In some investigations, the 1RM squat demonstrates a learning effect of up to 10 % with repeated testing sessions (Nuzzo *et al*. 2019). The reliability of 1RM in untrained populations tends to improve with the use of exercises that are performed in a fixed plane of movement (i.e. fewer degrees of freedom) such as a 1RM leg press (Nuzzo *et al*. 2019), presumably related to the differences in skill demand. However, practically speaking this seems like somewhat of a moot point as the conduct of maximal effort strength assessments in untrained populations in the field of generalised strength training seems ill-advised and unnecessary (Carpinelli 2011). 1RM testing can be quite a vigorous procedure, posing a level of risk that could be deemed unacceptable. 1RM testing has also been shown to increase muscle soreness and indirect markers of muscle damage (Arazi and Asadi 2013). This may be a concern for athletes as the exposure to such high loads may cause unnecessary fatigue, particularly if they are in-season athletes (Loturco *et al*. 2015; Loturco *et al*. 2016). Injury risk is often cited as a concern with 1RM testing, though much of this appears to be based on speculation and anecdote rather than empirical evidence. Notwithstanding, injuries to the knee joint have been reported following 1RM testing, albeit in elderly subjects (Pollock *et al*. 1991; Shaw *et al*. 1995).

Another factor that might be a consideration in the conduct of 1RM testing is the use of the stretch-shortening cycle, with faster eccentric tempos associated with greater weight lifted in upper body 1RM tests (Wilk *et al*. 2020). Additionally, a faster eccentric phase in the back squat is associated with a subsequent faster concentric phase at the same relative intensity (80 % of 1RM) (Carzoli *et al*. 2019). However, attenuating the stretch shortening cycle, such as in the case of the box squat exercise (performed by descending onto a box and pausing for 1 s before completing the concentric portion of the squat) does not appear to negatively impact performance compared to a traditional back squat (McBride *et al*. 2010). Overall, stretch-shortening cycle use and manipulation of velocity in the eccentric phase of the back squat may affect 1RM performance, though the extent to which is not well established.

Related to the point about the confounding effects of changes in joint angle throughout the movement, in tests such as the 1RM back squat, the range of motion can be difficult to control, which may in turn compromise the internal validity of the test. Moreover, judging the bottom position (specifically the lowest angle of the femur relative to the horizontal in the exercise, colloquially termed squat "depth") adds an element of subjectivity to the test, unlike other tests where the position and/or the range of motion are fixed, highlighting the potential for inter-rater variability when conducting this test. By contrast, in the example of the bench press exercise, the range of motion can be standardised by having the barbell make contact with the chest on every attempt, ensuring within-subject consistency of the range of motion. The squat is not constrained in the same manner, making it more difficult to standardise the range of motion. Anecdotally within the sport of Powerlifting, the judging of squat depth can be an issue of much contention, despite an objective criterion for squat depth readily available;

> *'bend the knees and lower the body until the top surface of*
> *the legs at the hip joint is lower than the top of the knees'*
> IPF, 2020

This is also observed within the literature, where there are clear inconsistencies in squat depths (Glassbrook *et al*. 2017). As no universal squat depth can be agreed upon, it is left to the discretion of the investigator. This creates a problem when comparing results across studies, as 1RM back squat tests performed to differing depths cannot be assumed to be equivalent. Data from Bazyler *et al*. (2014) demonstrate how the results of a 1RM squat test are highly influenced by squat depth. The authors tested 1RM back squat at two different depths, full (top of the leg at the hip joint being below the knee) and partial (80° of knee flexion) in a group of strength trained male subjects. 1RM weight lifted in the full depth squat was

148.2 (23.4) kg, whereas in the partial squat the subjects lifted 224.0 (40.1) kg. This exemplifies the influence of squat depth on the results obtained from a 1RM squat test as well as potential practical issues with depth standardisation. In investigations where it is not deemed necessary to attain full squat depth, some authors specify a modified squat depth (e.g. half squats) which helps in reducing discrepancies between studies and consequent confusion (Bogdanis *et al*. 2011). Overall, the issue of squat depth standardisation is one that may prompt researchers and practitioners to investigate alternatives to traditional 1RM testing.

In addition to the previous points that 1RM squat assessment is confounded by changes in joint angle throughout the movement as well as the depth chosen to conduct the assessment at, it can also be argued that the limiting factor in the 1RM squat is not the maximal force produced by the subject *per se* (i.e. the characteristic of interest) but rather the ability to overcome an external moment arm at a specific point or range within the concentric phase of the exercise, classically referred to as the “sticking point” (Hales *et al*. 2009; Carpinelli 2011; Van den Tillaar *et al*. 2014; Kompf and Arandjelović 2017). This is characterised by a distinct reduction in movement velocity and, if the exercise is performed to momentary muscular exhaustion, the sticking point is the point at which failure occurs (Kompf and Arandjelović 2017). For a full depth squat, the sticking point corresponds to a specific position in the concentric range of motion where the knee angle approximates 90° (McLaughlin *et al*. 1977). For a visual representation of the sticking point phenomenon, see Figure 1 below. An individual’s sticking point can never be eradicated as it is a function of their biomechanics (McLaughlin *et al*. 1977). However, improvements in technical factors that limit performance and overall efficiency in the back squat can contribute to overcoming the sticking point at a given barbell load (i.e. skill mediated factors) as opposed to specific neuromuscular adaptations that result in increased muscular force production (Carroll *et al*. 2001; Carroll *et al*. 2011). These technical factors may include improved thoracic, trunk and foot position as well as frontal knee position (i.e. decreased knee valgus) throughout the movement (Myer *et al*. 2014; Kushner *et al*. 2015). This skill related aspect of back squat performance is further evidenced by the aforementioned learning effect observed across repeated 1RM back squat testing sessions in untrained populations (Nuzzo *et al*. 2019). Hence, for a true assessment of muscular force production, a separate, less skill-dependent measure of lower body strength may provide valuable insight into the force production capacity of an individual. This is the overall framework in which an isometric multi-joint test (IMJT), such as the isometric squat (ISq) is proposed as a viable alternative or perhaps even a complimentary measure to 1RM testing (with the ISq providing an indication of lower body force production capacity, whereas the 1RM indicates specific strength in the back squat) and thus, the focus of this project. Recent evidence suggests there may be merit to the use of multiple measures of muscle strength, given the inherent advantages and limitations of the various modalities used to assess strength (Buckner *et al*. 2017; Nuzzo *et al*. 2019).

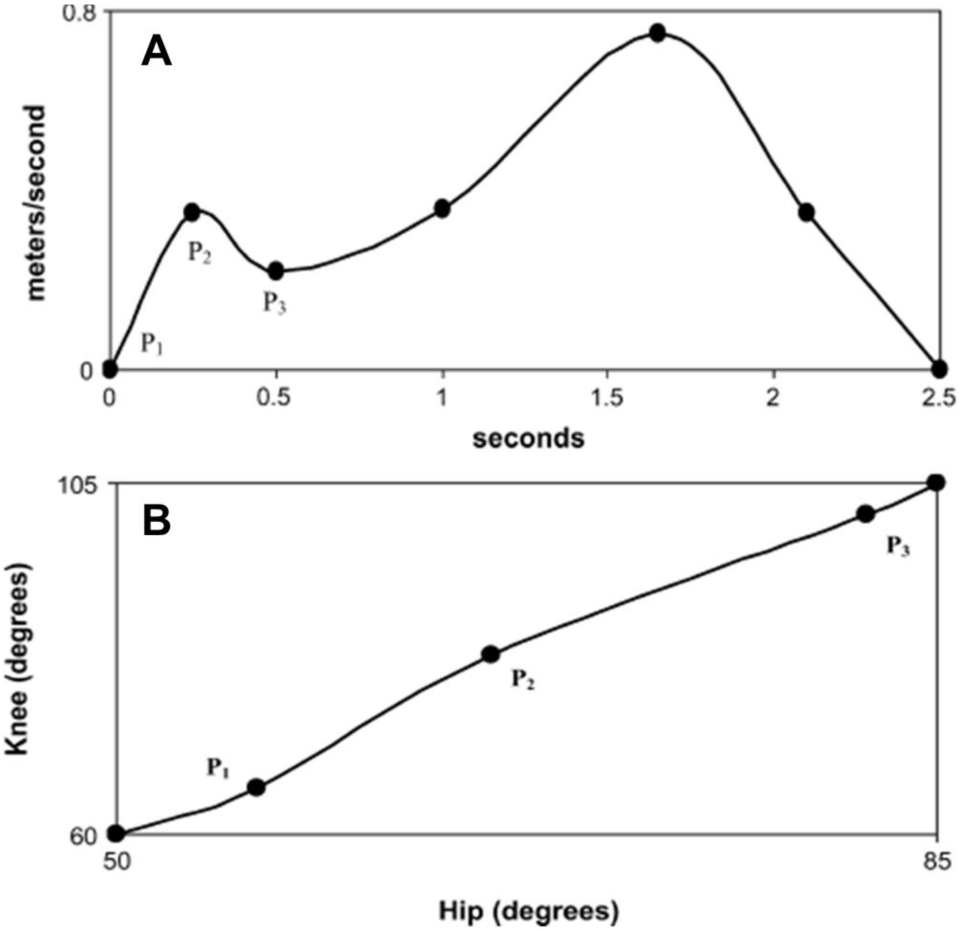

Figure 1 – Demonstration of the sticking point/region in the back squat exercise, adapted from Hales *et al*. (2009). **A** represents a typical velocity vs. time curve for a back squat brought to near momentary muscular failure. Following the initial increase (P_1 to P_2), barbell velocity decreases until reaching the nadir of the curve (P_2), before increasing again once the sticking point has been overcome (P_3). **B** represents an angle-angle curve demonstrating the knee and hip angle at the corresponding points in the velocity vs. time curve.

1.3 Rationale for the use of the isometric squat as a measure of lower body maximal strength

It is worth reiterating that each measure of maximal strength of the lower body carries inherent advantages as well as limitations and determining the appropriateness of a particular test is dependent on the context of the testing. A summary of the advantages and limitations of the various measures of maximal strength in the lower body is provided in Table 1.

Assessment mode	Knee extension Dynamometry [PF]	1RM back squat	Isometric squat [PF]
Internal validity	High	Questionable [1]	High
External validity	Low [2]	High	Moderate-high [3]
Reliability	High CV - 1.9-7 % [4] ICC - 0.902-0.998 [4]	Moderate-high * CV - 2.1-12 % [5, 6] ICC - 0.770-0.990 [7]	Moderate-high † CV - 4-14% [8, 9] ICC - 0.804-0.970 [8, 9]
Sensitivity	9-25 % [10, 11]	~ 5 % [12]	4-11 % [8, 13]
Setup costs	High	Low-moderate	High
Testers required	1-2	2-5	1-2
Skill requirement	Low [4]	High [6]	Low?

Table 1 – Summary of characteristics of lower body maximal force assessment modes. [1] Bryanton *et al*. (2012), [2] Abernethy *et al*. 1995), [3] Bazyler et al. (2015), [4] Maffiuletti *et al*. (2007), [5] Banyard *et al*. (2017), [6] Ribeiro *et al*. (2014), [7] Nuzzo *et al*. (2019), [8] Drake *et al*. (2018), [9] Palmer *et al*. (2017), [10] Sole *et al*. (2007), [11] Ferri-Morales et al. (2014), [12] Comfort *et al*. (2015), [13] Lum and Joseph (2019). [PF] = data are for peak force measurement only * = training status dependent, † = training status and position dependent. Note: sensitivity values based on the smallest change that indicates a real improvement.

The use of an IMJT provides an alternative measure that could be seen as a compromise between dynamic 1RM and isometric dynamometry. Comparable with isometric dynamometry, the IMJT allows for a highly controlled assessment of muscular strength by controlling for joint angle and movement velocity, suggesting strong internal validity. In addition, IMJT measures offer the ability to assess strength at key positions of certain dynamic strength training exercises, allowing them to retain a high degree of external validity. For example; the use of the IMTP in the position that corresponds with the second pull of the clean and snatch exercises (Haff *et al*. 1997) or the use of the ISq at a 90° knee angle, which very closely approximates the aforementioned sticking point in the back squat exercise (Bazyler *et al*. 2015). This is supported by a strong association between IMJT measures and dynamic 1RM tests, indicating high criterion validity (Bazyler *et al*. 2015; McGuigan *et al*. 2010; McGuigan *et al*. 2006).

The static nature of an IMJT likely reduces the skill demands of the task and this is presumably amongst the reasons why IMJT measures do not appear to be prone to systematic bias (Nuzzo *et al*. 2019). The two most frequently used IMJT measures are the IMTP and the ISq (Drake *et al*. 2017). Both tests have previously demonstrated high validity and reliability (Drake *et al*. 2017). Additionally, the use of a dual force plate system (depicted in Chapter 2, section 2.2) in the conduct of IMJT assessments allows for a separate analysis of force production of the individual limbs. This in turn allows for the analysis of inter-limb asymmetry in positions that are of relevance to overall performance (e.g. ISq assessment conducted at positions of relevance to 1RM back squat performance). Knowledge of the presence of marked inter-limb asymmetry may be worthy of consideration in future program design for an individual (e.g. specific strengthening exercises aimed at reducing inter-limb asymmetry) (Drid *et al*. 2009). The potential overall relevance of inter-limb asymmetry is discussed in section 1.5.

1.4 Establishing recommendations for preferred positioning in the conduct of isometric squat testing

Much work has been done in recent years to establish a standardised position for the IMTP that produces the greatest force output and reliability (Beckham *et al*. 2018; Guppy *et al*. 2019; Comfort *et al*. 2019). This is in contrast with the ISq, where despite an apparent sufficiency of ISq investigations in the available literature documenting the reliability of the measure, no standardised position has been recommended for the test. Measurement at a 120° knee angle (where 180° = full extension) has been commonly utilized in the available literature (Bazyler *et al*. 2015; Palmer *et al*. 2017). This stands to reason as it corresponds with the angle of peak torque generation during isolated knee extension (Thorstensson *et al*. 1976). The other most commonly used ISq position conducts the test at a 90° knee angle (Alegre *et al.* 2006; Pekünlü *et al*. 2014; Bazyler *et al*. 2015; Palmer *et al*. 2017; Drake *et al*. 2018), which approximates the aforementioned sticking point in the back squat (see Figure 1) and may be of interest to the practitioner. The preferred ISq position may differ depending on the context of the testing, so it is important to understand the characteristics of ISq measurement across different positions. For example, ISq tests that are performed at greater knee extension angles (i.e. > 90°) are easier to administer than lower ISq positions that require greater joint mobility. In addition, higher ISq positions produce greater peak isometric force (Palmer *et al.* 2017, Bazyler *et al.* 2015; Brady *et al.* 2018), which is of great relevance in the assessment of maximal lower body strength. In certain sporting contexts, ISq assessment in these positions could be quite insightful for practitioners given the biomechanical similarity between the positions. Using a practical example, consider the kinematics of a prop forward's positioning during a scrum (see Figure 2), which closely approximates the aforementioned 120° knee angle. This notion appears to be supported by the review of Green *et al.* (2019), who report the knee angle during scrummaging attempts at maximal sustained force ranges from 107-129°. In this context, assessment at a 120° knee angle could be of relevance to an athlete and/or coach.

Figure 2 – Knee joint kinematics of a prop during a scrum, approximating a 120° knee angle

By contrast, assessment at lower ISq positions (≤ 90° knee angle) place the athlete/subject in a more biomechanically disadvantageous position (Bazyler *et al.* 2015). Coupled with the fact that lower peak forces are observed here compared to ISq positions conducted at knee angles > 90° as well as the greater joint mobility demands (and potentially greater difficulty assuming these positions), this may deter some investigators from using such ISq positions. However in certain contexts, lower ISq positions may be of great relevance to the investigator. These will now be explored.

A 90° knee angle position approximates the sticking point (i.e. limiting factor) of the back squat exercise (McLaughlin *et al.* 1977; Van den Tillaar *et al.* 2014; Bazyler *et al.* 2015). Furthermore, current evidence indicates an association between force production in the ISq at a 90° knee angle and 1RM squat strength (Drake *et al.* 2018). This is supported by multiple observations of a strong correlation between either peak isometric force (PIF) or maximum force (MF, meaning the peak isometric force plus the subject body weight) in the ISq (performed at a 90° knee angle) and 1RM back squat weight lifted ($r \geq 0.7$, Table 2). Furthermore, the relative muscular effort of the knee extensors increases with decreased knee angle (or rather increased knee flexion) in the back squat (Bryanton *et al*. 2012), suggesting that ISq testing conducted at knee angles ≤ 90° may be a better indicator of 1RM squat strength compared to conducting the test at knee angles > 90°, as ≤ 90° appears to be the weakest region of the 1RM squat range of motion and thus could be considered more of a limiting factor for performance (see Table 2). Bazyler *et al.* (2015) reported a stronger correlation between 1RM back squat weight lifted and the ISq performed at a 90° knee angle ($r = 0.86$) compared to a 120° knee angle ($r = 0.6$). Although these correlations were not compared statistically, the findings suggest that when the ISq is performed at a 90° knee angle, it may be a better predictor of 1RM squat weight lifted, compared to a 120° knee angle. Taken together, the available evidence merits further exploration of the 90° knee angle, despite the lower peak forces observed compared to ISq positions that place the subject/athlete in greater degrees of knee extension. To the best of the author’s knowledge, only two studies provide hip angle data for ISq testing, rendering discussion of this variable difficult. Newton *et al*. (2002) report knee and hip angles of 90° and 110° respectively, whereas Brady *et al*. (2017) report mean knee and hip angles of 136° and 137° respectively. The reason for this lack of available hip angle data may be related to variability in subject anthropometry, whereby it is difficult to obtain the same knee and hip angles across a group of individuals due to differences in femur and torso length. Therefore, it stands to reason why only knee angle data are provided.

Current evidence suggests that the ISq is an extremely safe assessment of maximal strength. In the only study to date that documents an injury occurring during an ISq test, the test was performed at a 120° knee angle (Wilson *et al*. 1993). Furthermore, these authors raised concern about the rapid compression of the cervical vertebrae during the ISq test, with such forces likely to be higher at a 120° knee angle position compared to lower positions. However, given that only one out of the 64 subjects in Wilson *et al*. (1993) sustained an injury, coupled with an apparent lack of injuries reported during ISq testing across subsequent studies, the risk of injury during this type of assessment appears to be quite low. In addition, the rapid compression of the cervical vertebrae can be overcome by having the subject apply a minimal amount of pretension to the bar prior to the onset of the ISq contraction.

Author	**Subjects**	**1RM (kg)**	**ISq position**	**ISq force (N)**	**Correlation (r)**
Bazyler *et al.* (2015)	17 trained men	148 (23)	90° knee angle	2127 (265) MF	0.86
Blazevich *et al.* (2002)	14 trained men	162 (20)	90° knee angle	2,321 (No SD) MF	0.77
Demura *et al.* (2010)	15 trained men	99 (16)	"parallel"	Not provided	0.73
Drake *et al.* (2018)	36 trained men	196 (15)	90° knee angle	1592 (256) PIF	0.70
Nuzzo *et al.* (2008)	12 male athletes	171 (23)	140° knee angle	3522 (635) MF	0.63

Table 2 – Summary of correlations between isometric squat peak force and 1 repetition maximum back squat weight lifted [values presented as mean (SD)]. 1RM = One repetition maximum back squat, ISq = isometric squat, MF = maximum force (i.e. peak isometric force inclusive of subject body weight), PIF = peak isometric force (i.e. excluding subject bodyweight).

The use of the isometric squat in subjects of varying levels of strength and training experience

The ISq presents a credible alternative to 1RM back squat testing for the assessment of lower body maximal strength. As previously outlined, there are both practical and methodological concerns surrounding the conduct of the 1RM back squat, in addition to some concerns about the reliability of the measure in certain populations, particularly those who are not strength trained (Nuzzo *et al.* 2019). This may be due to the skill requirement of the 1RM back squat. By contrast, the ISq affords the ability to standardise the position in which the test is conducted, reducing both the degrees of freedom compared to the 1RM back squat and presumably, the skill requirement of the test. In addition, isometric contractions generate less fatigue (characterized by the inability to voluntarily generate or sustain a maximal level of force) compared to dynamic contractions (Cummins *et al*. 1991; Renaud and Kong 1991; Peltonen 2017), which may be appealing to practitioners. The ISq also appears to score highly for criterion validity, as evidenced by a strong correlation between ISq peak force and 1RM back squat weight lifted (see Table 2). Despite a number of investigations documenting the reliability of the ISq (Blazevich *et al*. 2002; Bazyler *et al*. 2015; Palmer *et al*. 2017; Drake *et al*. 2018), investigations of ISq reliability have predominantly been conducted on subjects of a very similar strength level and training experience (Brady *et al*. 2018). To the best of the author's knowledge, no previous study has investigated to what degree (if any) does maximal strength in the ISq (and/or the strength training status of an individual) affect the reliability of peak force measurement. The current thesis aims to investigate this relationship. Knowledge of this relationship may be of relevance to investigators who wish to conduct maximal strength assessments in subjects of varying levels of strength and training experience.

The sensitivity of the isometric squat to training-induced changes in maximal strength

Drake *et al*. (2018) conducted a direct investigation of the sensitivity of the ISq, concluding that an 11 % change in peak force output would be required to consider changes over time to be "real" (i.e. outside the error range of the test). However, this has not been explored longitudinally to determine in what context might one expect to attain increases in ISq peak force > 11 %. For instance, could this be achieved over the course of a short-term training intervention (e.g. 4-8 weeks long)? Or would longer training interventions be required? It remains to be seen if the proposed 11 % change could be achieved using ecologically valid (i.e. representative of typical practice) strength training. The sensitivity investigation of Drake *et al*. (2018) was also conducted in strength-trained individuals, which begs the question of whether or not the results could be extrapolated across a broader spectrum of training statuses. In addition, how might training-induced changes in maximal strength differ between ISq measured PIF and 1RM weight lifted (i.e. if both outcome measures are tested before and after a training intervention)? The answer to this question may be informative for both researchers and practitioners considering using the ISq.

The sensitivity of a test is dependent on its reliability, but it also extends to the ability of a test to detect change over time (Currell and Jeukendrup 2008). In the context of this research, this relates to the aforementioned capability of the ISq to detect strength training induced changes in maximal strength over time. For greater context, it was previously noted that typical dynamometry assessment scores highly for reliability and internal validity, but not external validity. In studies that incorporate ecologically valid strength training routines, the ability of dynamometry to detect changes in maximal strength performance when compared to that of 1RM weight lifted has been unconvincing. Following an 8 week training intervention, Murphy and Wilson (1997) observed divergent training induced changes in strength measured by isokinetic dynamometry (i.e. peak knee extension torque at 60° per second) and 1RM back squat weight lifted (4 % decrease vs. 21 % increase for isokinetic peak torque and 1RM back squat respectively). Others have observed a poor relationship between training induced changes in strength measured by dynamometry and 1RM. Sale (1992) observed increases of 29.1 % for 1RM leg press, with no change in peak isometric knee extension torque. Similar results were observed elsewhere for the 1RM bicep curl and isokinetic elbow flexion torque in response to training (no change vs. a 45 % increase in 1RM strength). Much of the disparity between these results can likely be explained by specificity, with the 1RM test possessing greater specificity to the exercises used in training. This is an important consideration for the ISq as a measure of maximal strength performance. The test would appear to have greater specificity to dynamic squatting type exercise compared to conventional dynamometry. A number of previous studies have investigated ISq measured changes in lower body maximal strength following strength training. Alegre *et al*. (2006) observed a 4.8 % increase in peak force following a 13 week training period which included half depth back squat training. Such an increase seems surprisingly low after 13 weeks of training in previously untrained individuals and this may be related to the training intensity prescribed for the intervention, which did not exceed 60 % of 1RM (Alegre *et al*. 2006). In contrast, Wilson *et al*. (1993) reported increases in ISq peak force of 14.4 % following a 10 week training protocol which included back squat training. However, no reliability data, indicating the change scores required to be considered real following training, were presented as part of this study. The divergent results of Alegre *et al*. (2006) and Wilson *et al*. (1993) may be better explained by the training protocols utilised rather than the overall sensitivity of the ISq. Currell and Jeukendrup (2008) recommend using a protocol known to improve performance in any investigation of sensitivity. In the context of this research, this can be applied by using a training protocol that will improve 1RM squat performance; the results of which can then be compared to changes in ISq measured PIF to determine the sensitivity of the measure to training induced changes in strength.

Lum and Joseph (2019) observed increases in peak force of 9.5 % and 15.9 % in the ISq at a 90° and 120° angle respectively following a 6 week strength training intervention. Analysis conducted prior to the training intervention revealed that change scores of 4.0 % and 4.8 % at (90° and 120° respectively) would be required following training in order to be considered real. However, their study did not compare results to that of other commonly used tests of maximal strength of the lower body (e.g. 1RM back squat). The current thesis aims to build on the work of Lum and Joseph (2019) by conducting a similar study that aims to determine the sensitivity of the ISq to detect strength training-induced changes in maximal strength, compared to changes in 1RM back squat weight lifted.

1.5 Use of the isometric squat to identify and monitor inter-limb asymmetry in force production

Use of a dual force plate ISq apparatus allows for the investigation of the total PIF as well as PIF of both the left and right limbs individually (Davies *et al*. 2018). This allows for the investigation of inter-limb asymmetry in ISq force production. Observation of inter-limb asymmetry in ISq measured PIF was made during the early phases of the experimental work, leading to further investigation about the potential utility of the ISq in detecting and monitoring inter-limb asymmetries in the ISq. This is explored in Chapter 6. Meaningful inter-limb asymmetries in various performance tests (i.e. percentage difference between limbs that are above a certain pre-determined threshold) have led researchers to speculate whether the presence of such asymmetries could be of detriment to performance and/or increase injury risk.

Inter-limb asymmetry in sport science and performance

Whilst the observation of asymmetries in various performance tests is an interesting one, this observation alone does not reliably infer whether or not these observed asymmetries are inherently undesirable or if they ought to be attenuated through targeted training (Bishop *et al*. 2018b). To further complicate matters, both the magnitude and direction (i.e. either the left or right presenting as the stronger limb) of observed asymmetry can vary depending on the performance test used to assess asymmetry, indicating a task specific nature of the phenomenon, rather than one test being entirely representative of inter-limb asymmetry (Bishop *et al*. 2018b). This point was recently demonstrated by Bishop *et al*. (2018b), who highlighted the task specific nature of asymmetries (magnitude and direction) as a function of the test employed (unilateral isometric squat, single leg countermovement jump and single leg broad jump). This suggests that practitioners should determine what performance tests (that are capable of detecting asymmetries) are of relevance to their athletes. Bishop *et al*. (2018b) recommend a test battery be employed to establish a more comprehensive view of an individual's level of task-specific asymmetry, and the choice of test/s should depend on the specific strength quality of greatest relevance to the sport (Jones and Bampouras 2010). Finally, in determining what tests to employ, associations with reductions in performance or heightened injury risk should also be considered (Bishop *et al*. 2017).

Asymmetry and its effect on injury risk

Inter-limb asymmetries of sufficient magnitude (> 10 % difference between limbs) are thought to increase injury risk. This notion may originally stem from the emphasis placed on establishing a minimum level of symmetry between limbs as part of a successful rehabilitation protocol following an injury. A cut-off of < 10% inter-limb asymmetry has been proposed as the target for rehabilitation for athletes returning to sport, although this has been chosen somewhat arbitrarily and may not lower the risk for re-injury sufficiently (Wellsandt *et al*. 2017; Bishop *et al*. 2018a). Along similar lines, it is difficult to establish a causal relationship between asymmetry and injury as the link between inter-limb asymmetry and injury risk is not consistent. Bennell *et al*. (1998) found no link between inter-limb asymmetries in hamstring strength (measured via isokinetic dynamometry) and hamstring injury risk in a group of Australian rules football players. However, the magnitude of asymmetry between hamstrings was not particularly high (≤ 4 % difference in peak torque between legs). By contrast, when inter-limb asymmetries in isokinetic hamstring strength are of greater magnitude (≥ 9 %), they have shown to be predictive of future hamstring injury in Australian footballers (Orchard *et al*. 1997).

Previous research has attempted to establish an inter-limb asymmetry cut-off (or threshold) that could be considered meaningful in the context of identifying an increased risk for injury in athletes. However, given the widely differing methodologies employed between studies (particularly with respect to the type of test used to assess asymmetry), drawing confident conclusions about any minimum cut-offs becomes extremely difficult. Furthermore, as previously noted, inter-limb asymmetry thresholds have been proposed as targets for athletes rehabilitating from injury, yet these may not lower the risk for re-injury sufficiently (Wellsandt *et al*. 2017;

Bishop *et al*. 2018a). Therefore, applying asymmetry thresholds to uninjured athletes aimed at predicting future injury ought to be met with extreme scepticism given the current evidence available. The aforementioned 10 % cut-off has been proposed as a threshold for increased injury risk, although this has not demonstrated reliable predictive ability (Grace *et al*. 1984). Conversely, asymmetries ≥ 15 % in isokinetic hamstring strength were predictive of injury in a group of 687 professional soccer players (Croisier *et al*. 2008). Interestingly, the risk was reduced in those who received subsequent “compensation training” for the weaker limb, compared to those who did not. This suggests some merit to the idea of targeted training to reduce inter-limb asymmetry. There are additional data to support the hypothesis of ≥ 15 % as being predictive of future injury. Knapik *et al*. (1991) found that females athletes (from various sporting disciplines) with ≥ 15 % difference in isokinetic hamstring strength between limbs at baseline sustained more injuries than those with isokinetic hamstring strength asymmetries < 15 % over the course of a 3 year period. However, these links are merely associative and in contrast with Croisier *et al.* (2008), no compensatory training was performed by any of the subjects, meaning that it is unclear if injury rates could be reduced with training interventions designed to attenuate observed asymmetries in strength. Finally, Bell *et al*. (2014) reported that an observed power asymmetry (in the countermovement jump) of > 10 % placed athletes at a “high risk of injury” in their study of mixed team sport athletes, suggesting that the previously indicated > 15 % threshold may be too high of a cut-off to use in this context. However, it cannot be reasonably assumed that an observed asymmetry in one test is equivalent to an asymmetry in another test (in this example a countermovement jump vs. isokinetic dynamometry). Overall, the state of the evidence is probably best summarized by Hewitt *et al*.

(2012) who conclude that whilst no specific magnitude of asymmetry has been identified to date, magnitudes of < 10 % are typically observed in un-injured populations. Furthermore, athletes who present with inter-limb asymmetries ≥ 15% may not necessarily incur an injury, and those below this threshold are not guaranteed to avoid injury (Hewitt *et al*. 2012). Overall, aiming to achieve an inter-limb asymmetry of < 10 % may be prudent for minimizing the potential injury risk associated with the phenomenon.

Inter-limb asymmetry and the potential for decrements in performance

According to Bishop *et al*. (2018a) the majority of the current literature only serves to document the presence of inter-limb asymmetries, rather than identifying whether or not these asymmetries have any impact on performance. Based on currently available literature, asymmetry does not appear to be detrimental to performance, at least not in all contexts (Maloney 2019). Bell *et al*. (2014) found that ≥ 10 % inter-limb asymmetry in countermovement jump peak force resulted in reduced jump height in a group of male and female student athletes. Isometric mid-thigh pull (IMTP) asymmetries were negatively correlated with squat jump (r = -0.52) and countermovement jump height (r = -0.47) in a group of collegiate athletes (Bailey *et al*. 2013). This suggests some (albeit tenuous) association between inter-limb asymmetry in force production and reduced performance, which in turn could be attenuated through a targeted training intervention. Conversely, any conclusions made about such modest correlations between asymmetries and performance should be very cautious. It is also possible that jump performance could be improved as a result of increasing overall strength, with or without a concomitant change in asymmetry.

Asymmetry scores from squat jump and countermovement jump tests were not associated with reduced performance (30-m sprint, change of direction and squat jump power output tests) in a group of female soccer players (Loturco *et al.* 2019). However, when a similar protocol was employed in a group of male youth handball players, sprint and change of direction performance were negatively correlated with asymmetry scores across a series of jumping, change of direction and isoinertial tests (Madruga-Parera *et al*. 2019). Moreover, strength, jumping and change of direction asymmetries were not associated with reduced performance in elite academy soccer players, despite rather large asymmetries observed in some of the performance tests (11.9 % and 21.2 % asymmetry for vertical and lateral jump respectively). Much like in the cases of Bell *et al*. (2014) and Bailey *et al*. (2013), relating the influence of an observed asymmetry in one test to perform in another seems somewhat dubious and ought to be interpreted with scepticism. Overall, the available literature serves to highlight that

1. Inter-limb asymmetries are highly task and variable specific.
2. The role that asymmetry may play in performance remains unclear.

Specificity of inter-limb asymmetry - not all asymmetries are created equally

As previously noted, asymmetry scores are test specific. In addition, current evidence suggests that asymmetries are also variable specific (e.g. peak force, early phase rate of force development, impulse etc.) in magnitude and sometimes in direction (i.e. stronger right or left side). Kuki *et al*. (2019) reported significantly greater asymmetry scores in the bilateral IMTP compared to the unilateral IMTP (24 % vs. 10 % asymmetry respectively). Within the same test (e.g. IMTP, isometric dynamometry etc.), asymmetries in isometric strength tend to be of greater magnitude (i.e. > 10 %) for early phase rate of force development (RFD) variables compared to peak force (< 10 %) or late RFD (< 15 %) variables (Bishop *et al*. 2019; Sarabon *et al*. 2020). It should be noted however that early phase RFD data also tends to be less reliable (CV > 10 %) compared to late phase RFD (CV < 5.5 %) or peak force (CV < 5 %) data (Buckthorpe *et al*. 2012; Tillin *et al*. 2011), which in turn affects the interpretation of an observed inter-limb asymmetry score.

In perhaps the most insightful study of this variation in asymmetry magnitude and direction across different performance tests, Bishop *et al*. (2018b) document the individual variability in asymmetry magnitude and direction in the unilateral isometric squat, single leg countermovement jump and single leg broad jump (as shown in Figure 3). In addition, data from Bishop *et al*. (2020) show that the magnitude and direction of asymmetry (countermovement jump and drop jump) can fluctuate over the course of a competitive soccer season, making the interpretation of the overall relevance of asymmetry scores even more difficult for the strength and conditioning professional who may consider employing a particular training intervention aimed at addressing such asymmetries.

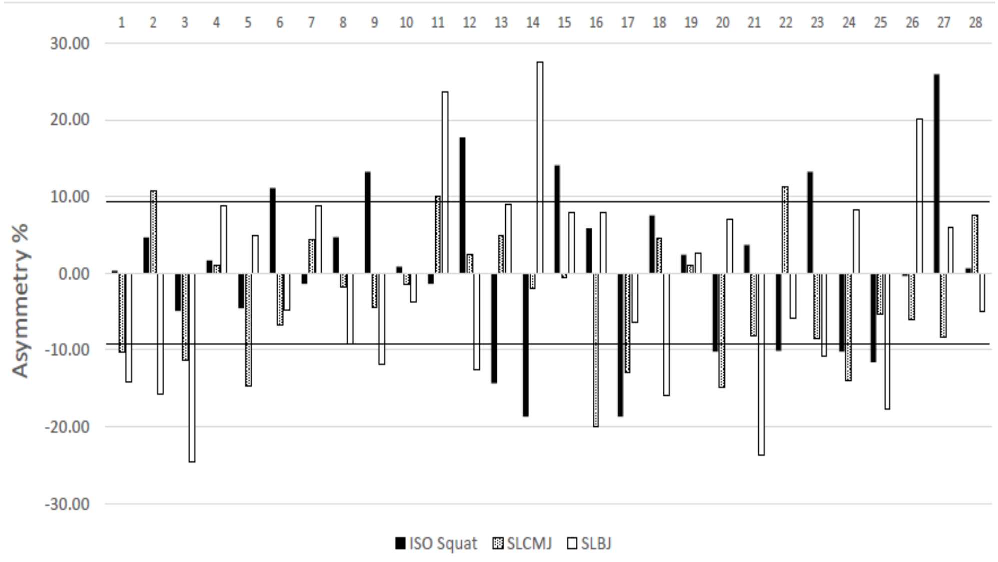

Figure 3 - Individual asymmetry data for peak force (PF) during the isometric squat (ISO Squat, CV = 5.7 %), single leg countermovement jump (SLCMJ, CV = 5.8 %) and single leg broad jump (SLBJ, CV = 9.3 %). Positive values indicate a stronger right limb, negative values indicate a stronger left limb. This figure is taken from Bishop *et al*. (2018b).

Classifying sporting asymmetries and establishing a rationale for this paradigm

According to Maloney (2019) motor tasks can be divided into four categories, which correspond with differing sporting demands. These classifications build on previous work from Guiard (1987) and are as follows:

1. Unilateral (i.e., long jump take off)
2. Bilateral asymmetric (i.e., golf swing)
3. Out-of-phase bilateral symmetric (i.e., cycling)
4. In-phase bilateral symmetric (i.e., weightlifting, powerlifting)

This framework may help to infer what performance tests with the ability to detect asymmetries may be of greatest specificity to a particular athletic population. For example, if an athlete presents with a marked asymmetry in a sport where unilateral motor tasks predominate, there may not be sufficient grounds for interpreting this as detrimental to performance and by extension, something that the practitioner ought to address with training. Hart *et al.* (2020) documented significantly greater bone strength and cross sectional area of the support leg (i.e. non-preferred kicking leg) of professional Australian rules players, concluding that these asymmetries are a function of the differing demands placed on a players legs. In this context, it would stand to reason that inter-limb asymmetry is simply a product of the differing function of the limbs over time and not detrimental to performance.

By contrast, in sports where force is produced bilaterally and symmetrically (class 4 motor tasks under the above categorization), an observed inter-limb asymmetry in force production may indicate a potential adaptation window of opportunity whereby if the force output of the stronger limb is at least maintained whilst that of the weaker limb increased, the overall performance (combination of both limbs producing force simultaneously) would increase. A visual representation of this theoretical concept is shown in Figure 4, which is adapted from Maloney (2019). In the context of performance, observation of a marked inter-limb asymmetry may bear relevance to overall performance. In this paradigm, a bilateral test of inter-limb asymmetry such as the ISq may be appropriate to use. The ISq has previously been used to monitor changes in inter-limb asymmetry following a training intervention (Bazyler *et al*. 2014). Moreover, training induced reductions in inter-limb asymmetry were associated with increased PIF in the ISq and 1RM squat weight lifted. Taken together, this provides a reasonable theoretical rationale for the use of the ISq in this manner, as it may have the ability to detect asymmetries in force production, which could be detrimental to performance based on the framework proposed by Maloney (2019), whereby the performance in the bilateral test is equal to the force produced by the individual limbs simultaneously. Following the identification of such asymmetries, the next question of interest is whether or not these can be attenuated using ecologically valid strength training. The work of Bazyler *et al*. (2014) shows promise in this area, though it is the only study of its kind that has used the ISq in this specific application. As such, this thesis aims to investigate the use of the ISq to identify inter-limb asymmetry as well as monitor changes in inter-limb asymmetry following distinct strength training interventions.

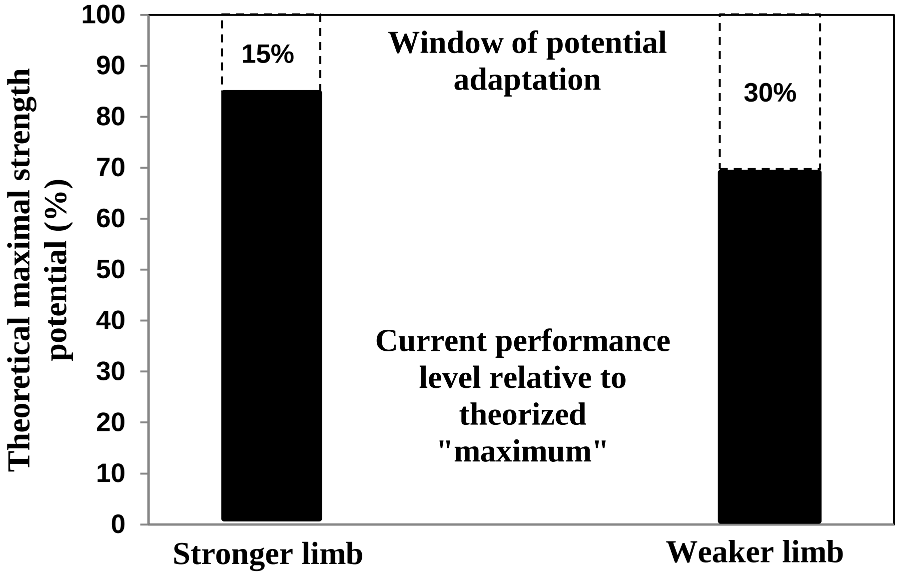

Figure 4 - A theoretical basis for deleterious effect of marked bilateral strength asymmetry on overall bilateral strength performance, taken from Maloney (2019).

Evidence for reduction of inter-limb asymmetry with training

There is a paucity of literature in the area of training-induced attenuation of inter-limb asymmetry amongst non-injured individuals, with widely divergent training methodologies employed, but the evidence that is available shows some promise. The previously mentioned study by Croisier *et al*. (2008) demonstrated a reduction of inter-limb asymmetry in isokinetic hamstring strength (via compensation training to bring hamstring strength asymmetry < 5 %), which was associated with reduced a likelihood of future hamstring injury. The training consisted of isolated manual, isotonic, or isokinetic strengthening for the weaker hamstring. In a case study (n = 1) by Brown *et al*. (2017), targeted hip extension training (incorporating supplemental unilateral strengthening and jumping exercises for the weaker leg in addition to their typical bilateral strength training) led to improved force production symmetry as well as improved maximal velocity and power during sprinting, following a 6 week intervention period. Balance and stability training has also shown positive results on inter-limb asymmetries (Sannicandro *et al*. 2014; Appleby *et al*. 2020). The aforementioned training study of Bazyler *et al*. (2014) may be of greatest relevance in the context of the proposed paradigm. Changes in inter-limb asymmetry were assessed using the ISq, in conjunction with peak force in the ISq and 1RM weight lifted. Subjects were divided into strong and weak sub-groups based on their ISq peak force values at baseline, with greater asymmetry scores observed amongst weaker subjects. All subjects followed a 7-week, periodized back squat training protocol. Significant reductions in asymmetry were observed in the “weaker” sub-group following training, in conjunction with significant increases in peak force (at a 120° knee angle) and 1RM. However, whilst no changes in asymmetry scores were observed in the "stronger" subjects following training, the subjects in this sub-group also experienced significant increases in peak force and 1RM. This suggests that the observed link between reductions in asymmetry and increased strength performance following training may be associative and not necessarily causal. Building on the work of Bazyler *et al*. (2014), it would be interesting to see if similar results could be obtained using divergent training protocols, such as the use of unilateral lower body strength training, as distinct from bilateral back squat training.

1.6 Conclusions and aims

Effective assessment of maximal lower body strength carries many complexities and nuances depending on the purpose and application of testing. This thesis will focus on the assessment of lower body maximal force production in the context of performance assessment in uninjured, male individuals of varying levels of strength and training experience. Central to the theme of effective lower body maximal strength assessment are the criteria outlined in section 1.1, as well as the characteristics of the different strength assessment modes outlined in section 1.2. Consideration of the criteria for effective performance assessment in a given test should allow researchers and practitioners alike to make a more informed choice about the most suitable mode of assessment to use in the context of performance assessment, given the particular advantages and constraints of each. In the preceding sections the rationale for the use of the ISq as a measure of lower body maximal strength is presented, whilst also highlighting a number of areas where the available literature is currently lacking. As such, this thesis aims to contribute to the knowledgebase by investigating these areas empirically. Specifically, the aims of this thesis are as follows:

1. To establish the preferred position(s) in which to conduct the ISq based on within day and between day reliability.
2. To investigate the influence of maximal strength in the ISq on the reliability of the measure.
3. To determine the sensitivity of the ISq to detect strength training induced changes in lower body maximal strength as measured by PIF.
4. To investigate the use of the ISq to detect and monitor changes in inter-limb asymmetry in response to strength training.
5. To compare the impact of unilateral and bilateral strength training on inter-limb asymmetry.

Chapter 2

2.0 Methods and procedures

2.1 Subjects

2.1.1 Recruitment

All subjects were recruited from the local area via word of mouth as well as social media and email advertisement.

2.1.2 Eligibility criteria

Study 1

The eligibility criteria for study one was as follows (these were also common to all subsequent interventions):

(i) Male
(ii) 18 to 35 years of age,
(iii) Habitually active and in good general health with no current injuries, illness or history of disease.

No specific strength training experience criteria were stipulated for this study.

Study 2

As study two sought to investigate the influence of maximal strength on ISq reliability, a mixed sample of subjects with varying levels of strength and strength training experience were recruited, using the follows operationally defined categories:

(i) Untrained individuals - no prior strength training experience
(ii) Moderately trained individuals - required to have a minimum of six months of strength training experience and 1RM back squat that did not exceed 1.5 × body mass.
(iii) Highly trained individuals - these were competitive Powerlifters with a minimum of 3 years of strength training experience and a competition 1RM back squat of ≥ 2 × body mass that was performed within 3 months of participation in the study.

Studies 3 and 4

Studies three and four were conducted on moderately trained subjects, as outlined in the criteria for study two.

2.1.3 General subject setup and anthropometry

Following written informed consent, initial acquaintance with the ISq (and if applicable the 1RM) apparatus as well as a full explanation of the test procedures (undertaken 24 to 72 h prior to starting the study) each subject reported to the lab to conduct the testing procedures. Subjects reported to the lab each test day at the same time to minimize any influence of diurnal variation on strength (Grgic *et al*. 2019). Dietary intake was recorded prior to the first test day and each subject was instructed to repeat this intake before the second test day. Subjects were also instructed to refrain from caffeine intake prior to each test session, given the potential for this to confound test results (Warren *et al*. 2010; Grgic *et al*. 2018). In addition, subjects were instructed to refrain from any formal lower body exercise 48 h prior to testing. Height and body mass were recorded using a stadiometer (Seca, UK) and a weighing scales (Seca, UK) respectively.

2.2 Isometric Squat

2.2.1 Apparatus

Isometric squat (ISq) testing was conducted using a custom-made ISq rack (Odin Gym Equipment, Ireland) with a fixed barbell, adjustable in height, positioned above two force plates (AMTI, Watertown MA). The rack was bolted to the floor around the force plates (see Figure 5). Note that the two force plates allowed for the assessment of inter-limb asymmetry in force production.

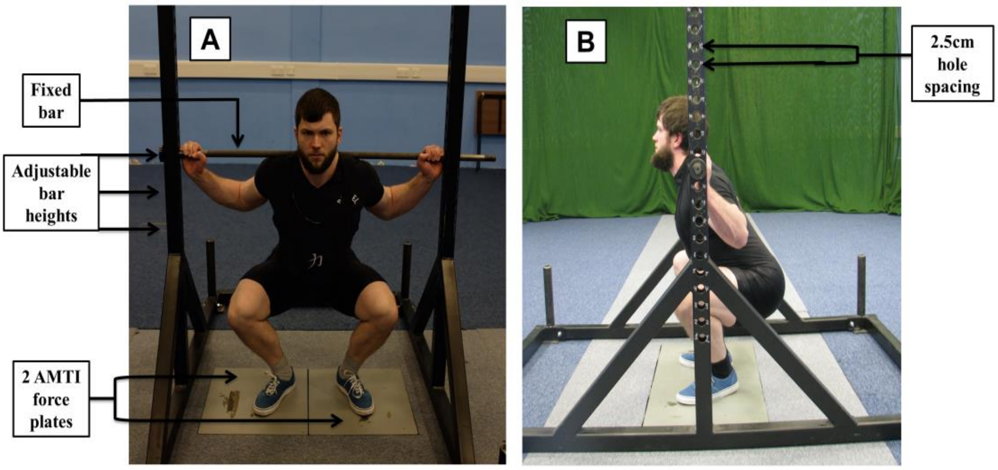

Figure 5 – Isometric squat rack apparatus with a subject in the isometric squat position. **A** = front view, **B** = side view. In this example the isometric squat was performed with knee and hip angles of 65° and 115° respectively.

2.2.2 Subject setup

The subjects removed their shoes for the duration of the test procedure to control for any variation in footwear between subjects or between test sessions. Prior to commencing the warm up, the rack heights that corresponded to the required ISq test positions were obtained. To do this the subject assumed their preferred squatting position (i.e. stance width and foot position) on top of the force plates. The distance between the feet at the anterior (i.e. distance between the two first distal phalanges) and posterior extremities (i.e. distance between the most posterior and medial aspect of the left and right calcaneus bones) was measured, recorded and marked with tape. For repeat trials, tape was re-laid using the measurements recorded in the first testing session, allowing for consistency across trials. Whilst maintaining this same squatting stance, each subject was then instructed to descend until the desired knee angle was obtained. The knee angle was measured using a plastic goniometer (Fabrication Enterprises, NY) which was placed on the lateral condyle of the femur, the fixed end was aligned with the greater trochanter of the femur, and the moving arm aligned with the lateral malleolus of the ankle.

For the purpose of this thesis, up to three isometric squat positions were used throughout the experimental work, depending on the investigation. The three positions were (note that 180° was considered full knee extension):

(i) 120° knee angle (ISq_{120}), as shown in Figure 6 A. This position is commonly used in ISq research, with previous investigations documenting high test-retest reliability (i.e. CV < 10 % and/or ICC > 0.8) in this position (Blazevich *et al.* 2002; Tillin *et al.* 2013; Bazyler *et al.* 2015; Lum and Joseph 2019).

(ii) 90° knee angle (ISq_{90}), see Figure 6 B. This position was chosen because of its previously documented strong correlation with 1RM squat (r = 0.7-0.86) (Blazevich *et al.* 2002; Bazyler *et al.* 2015; Drake *et al.* 2018). Presumably, this is because the ISq_{90} approximates the sticking region of the back squat exercise (Bazyler *et al*. 2014; Bazyler *et al*. 2015; Drake *et al*. 2018). Based on this evidence, the ISq_{90} may serve as a suitable proxy measure for the 1RM squat.

(iii) 65° knee angle (ISq_{65}), where the greater trochanter of the femur is below the level of the superior border of the patella (Figure 6 C). To date no prior study of the ISq has investigated the utility of positions below that of a 90° knee angle and because if this, the reliability of the ISq_{65} is currently unknown. The ISq_{65} position approximates the knee angle observed in the bottom position of the back squat in powerlifting under maximal loads (Hales *et al.* 2009; Swinton *et al.* 2012) and is considered the criteria for full squat depth by the International Powerlifting Federation (IPF, 2020). As such, the ISq_{65} corresponded with the position obtained at the bottom of the 1RM back squat test.

The accuracy of the isometric squat (ISq) positioning was limited by the 2.5cm spacing between rack heights (see Figure 5), meaning some between-subject variation in positioning occurred (± 5°). However, the procedure ensured within-subject consistency across all trials.

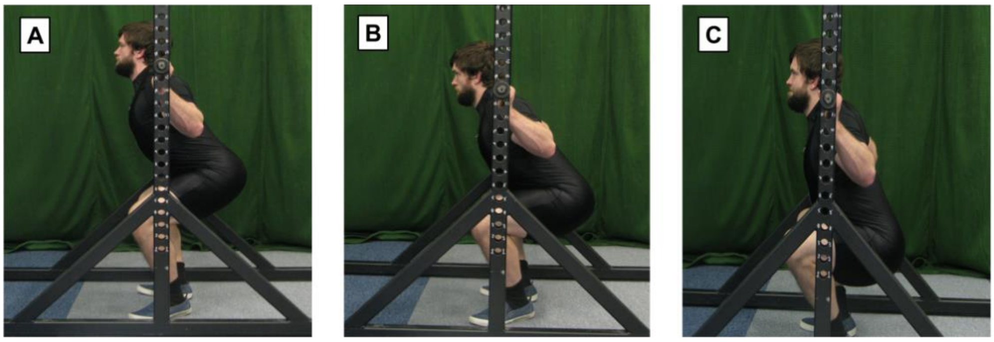

Figure 6 – Isometric squat positions used throughout the experimental work contained in this thesis. **A** = 120° knee angle (ISq$_{120}$), **B** = 90° knee angle (ISq$_{90}$), **C** = 65° knee angle (ISq$_{65}$). Note that the accuracy of the knee angles was limited by the 2.5 cm hole spacing between isometric squat rack heights.

2.2.3 Warm up

Subjects began a standardised warm up procedure with 5 min of cycling exercise at a power output of 90 watts (~60 RPM) on a cycle ergometer (Monark, Sweden). Subjects were allowed to perform any brief dynamic stretches (e.g. bodyweight squats) they wished to before beginning the test procedure. In study one; subjects performed the ISq in all three positions, beginning with the ISq$_{65}$, followed by ISq$_{90}$ and then ISq$_{120}$, in a similar manner to the procedures used by Beckham *et al*. (2012) for the isometric deadlift. This ensured consistency across both test days. All other investigations used the ISq$_{120}$ and ISq$_{90}$, and the order of the positions was randomly allocated to each subject on their first test day. This sequence was then repeated on each subsequent trial.

Once the first position was allocated, the rack was set at the required height and the subjects assumed the ISq position under the fixed barbell. Subjects were then instructed on the procedure for the ISq test; to push into the bar and the force plates as if they were performing a regular barbell squat. Subjects completed three warm up ISq in the first position prior to measurement (50 %, 70 % and 90 % of perceived maximal effort) which were maintained for at least 3 s with a 1 min rest between each ISq. In between sub-maximal trials, feedback was provided to subjects on the quality of the sub-maximal ISq contractions that they produced; namely, the presence of any countermovements, deviation from the position that was established during the setup, failure to maintain a stable baseline prior to initiating the contraction. This is described in greater detail later on in section 2.2.6. In addition, the sub-maximal trials were also used to ensure that subjects achieved PIF as fast as possible. If ramping (i.e. a gradual increase in the force-time curve up to PIF) occurred on a sub-maximal trial, the subject was instructed to achieve PIF as fast as possible, with the curve shown to help instruct the subject on exactly what was required. Following the last warm up trial, a 2 min rest period was provided. This is the recommended warm-up procedure for isometric strength testing of this nature (Comfort *et al.* 2019).

2.2.4 Maximal effort trials

Instructions given to subjects

Given the overall relevance of RFD in strength testing (Maffiuletti *et al*. 2016; Rodríguez-Rosell *et al*. 2017), coupled with the fact that the force–time curve derived from the ISq allows for the analysis of this variable; it was decided to assess the reliability of RFD as well as PIF in the ISq. However, because maximal strength was considered to be of greatest importance for the purpose of this research (as distinct from explosive strength), the instructions provided to subjects reflected this consideration.

For each maximal effort ISq all subjects were given standard verbal encouragement from the investigators. Subjects were instructed to “push as hard and fast as possible into the bar” and to maintain peak force output for a minimum of 3 s. Typically, this meant that contractions lasted between 4 and 5 s. Several lines of evidence suggest that the instructions given to subjects prior to test execution can affect the data obtained from an isometric strength test (Rodriguez-Rosell *et al*. 2017). Sahaly *et al*. (2001) had subjects perform a seated bilateral isometric leg press exercise under two differing conditions of instruction. Under instruction 1 subjects were told to perform the contraction as “*hard and fast*” as possible. Under instruction 2 subjects were instructed to perform the contraction as “*fast*” as possible. Instruction 1 led to higher PIF values (instruction 1 = 3994 (767) N, instruction 2 = 3878 (819) N, $P < 0.001$). However, RFD was greatest following instruction 2 (instruction 1 = 9739 (4290) $N \cdot s^{-1}$, instruction 2 = 14189 (5396) $N \cdot s^{-1}$, $P < 0.01$). These findings were replicated by Sahaly *et al*. (2003), who additionally noted that the greater RFD values obtained under the “*fast*” instructions could be explained by higher EMG values, suggesting greater activation of the knee extensors. Jaafar and Lajili (2018) found that knee extension PIF was relatively unaffected by instruction type (“*hard and fast*” instruction = 697.7 (117.2) N, “*fast*” instruction = 698.4 (128.6) N, $P > 0.05$), whereas RFD was significantly affected by instruction type (“*hard and fast*” instruction = 3917 (907) $N \cdot s^{-1}$, “*fast*” instruction = 5880 (1066) $N \cdot s^{-1}$, $P < 0.001$).

The findings of Drake *et al*. (2019) indicate that ISq instructions not only affect the magnitude of force variables, but also their reliability. This is of greatest relevance to this research, given the interest in ISq measurement reliability. Based on the findings of Drake *et al*. (2019), it appears that separate procedures ought to be followed for obtainment of maximal strength (i.e. PIF) and explosive strength (i.e. RFD) data. The procedures for obtaining the highest PIF vs. RFD differ in terms of duration (3 vs. 1 s contraction length for maximal PIF vs. RFD respectively) and the instructions provided ("*push against the bar as hard and as fast as possible*" vs. "*push against the bar as fast and as hard as possible*" for maximal PIF vs. RFD respectively). Drake *et al*. (2019) found higher PIF values were obtained with the "*hard and fast*" instructions and a 3 s contraction compared to the "*fast and hard*" instructions and a 1 s contraction at both a 100° ("*hard and fast*" PIF = 2013 (251.7) N; "*fast and hard*" PIF = 1791 (315.5) N) and a 125° knee angle ("*hard and fast*" PIF = 2904 (408.8) N; "*fast and hard*" PIF = 2393 (337.0) N). Conversely, as previously noted the RFD values not only improved as a function of the procedures, but reliability was also improved substantially at both the 100° ("*hard and fast*" RFD 0-250ms = 3828 (1237) $N \cdot s^{-1}$, CV = 25.2 %; "*fast and hard*" RFD 0-250ms = 5551 (984) $N \cdot s^{-1}$, CV = 6.2 %) and 125° knee angle ("*hard and fast*" RFD 0-250ms = 5577 (1662) $N \cdot s^{-1}$, CV = 19.2 %, "*fast and hard*" RFD 0-250ms = 7276 (1342) $N \cdot s^{-1}$, CV = 5.2 %).

These data suggest that if RFD were of greatest interest to an investigator, then separate testing procedures ought to be carried out. With this in mind, it is acknowledged that the RFD data outlined within this thesis are compromised; a delimitation of this research project. Considering that up to three positions were used for ISq testing as well as 1RM testing in two of the studies contained within this thesis, conducting separate procedures to collect RFD data would likely be excessive and affect subjects' fatigue and motivation levels during testing sessions.

Immediately prior to each ISq contraction, subjects were instructed to apply a minimal amount of pre-tension into the bar in order to close the space between the bar and the holes in the rack and to help prevent any countermovement at the start of the contraction. This was monitored by visual inspection of the subject and the force read. Once the subject tensed against the bar, the force read was zeroed. At the onset of the audible cue the contraction started and subjects were encouraged by the experimenters to maintain the peak force (a standardised "*push, push, push*…" for the duration of the 3 s contraction). Three maximal effort contractions were performed in each ISq position, with 3 min rest given between each attempt to minimize fatigue accumulation (Willardson 2006), in-line with rest periods provided in previous ISq testing research (Brady *et al*. 2017; Drake *et al*. 2018). A TV screen mounted in front of the ISq rack allowed subjects to view the force read. Providing visual feedback to subjects has been shown to improve PIF values (Amagliani *et al*. 2010). This was also helpful in the event that a contraction was of inadequate quality (e.g. unsteady baseline or countermovement) as the subject could be shown exactly what happened and more easily understand how to correct it. Contraction quality was assessed after the testing session (as outlined in detail later on in section 2.2.6). However, in the event that an ISq contraction was immediately deemed unacceptable, then an additional trial was performed. An example of this is a very obvious countermovement, detected from visual inspection of the force read (> 50 N deviation from the baseline force read immediately prior to contraction initiation, discussed in greater detail later in section 2.2.6).

2.2.5 Maximal isometric squat testing and obtaining force variables of interest

Cortex motion analysis software (Rohnert Park, CA) was used for the collection of the ISq force-time curve data. For each contraction, ground reaction force data were sampled at 1 kHz. It was decided not to apply any data filtering, as current evidence suggests filtering of isometric force-time curve data reduces peak force values by a trivial but significant ($P < 0.001$)

amount, with no effect on reliability (Dos'Santos *et al*. 2018; Moir *et al*. 2019). Additionally, no smoothing techniques were utilized as no consensus regarding optimal smoothing of isometric force-time curve data currently exists (Comfort *et al*. 2019). An example force-time curve is presented in Figure 7. PIF, the variable of greatest interest for the purpose of this thesis was determined as the highest value recorded from the entire force-time curve (excluding subject body weight, as indicated in Figure 7). As indicated in Table 2 of Chapter 1, maximum force (MF; the peak isometric force inclusive of subject body weight) is commonly reported in the literature.

Time-constrained force variables were also obtained from the trace, though as outlined earlier (section 2.2.4) these ought to be interpreted with caution. RFD was calculated by dividing the change in force by the change in time (RFD = Δ Force/Δ Time), expressed in $N \cdot s^{-1}$ (Chavda *et al.* 2020). Typically RFD is calculated by dividing the change in force over specified time bands (0 – 50, 0 – 100, 0 – 150, 0 – 200, 0 – 250 ms) (Haff *et al.* 2015; Brady *et al.* 2017). Additionally, the "peak RFD" can be determined as the highest RFD during a pre-determined sampling window, of which 20 ms has previously demonstrated acceptable reliability (CV = 12.7 %, ICC = 0.9) compared to other sampling windows (2, 5, 10, 30 and 50 ms). Average RFD is calculated by putting the highest PIF value over the time interval from the initiation of the contraction to time-point at which the peak force value occurs (i.e. from the grey circle to the black circle in Figure 7). However this value has demonstrated poor reliability (> 20 % CV) from previous IMJT protocols (Haff *et al.* 2017; Brady *et al.* 2017). The reliability of RFD in the ISq is presented in study one (Chapter 3), using the 0-250ms time band. This was chosen because larger time bands (e.g. 0-200ms, 0-250ms) have previously been shown to provide more reliable data (CV < 10 %, ICC > 0.85) compared to shorter (e.g. 0-50ms, 0-100ms etc.)

time bands, which typically display poorer (CV > 10 %, ICC < 0.85) reliability (Brady *et al*. 2017; Buckthorphe *et al*. 2012; Maffiuletti *et al*. 2016). In addition, larger time bands appear to be better related to PIF compared to shorter time bands (Andersen and Aagaard 2006; Maffiuletti *et al*. 2016). Force onset was identified manually, as outlined by Tillin *et al*. (2010).

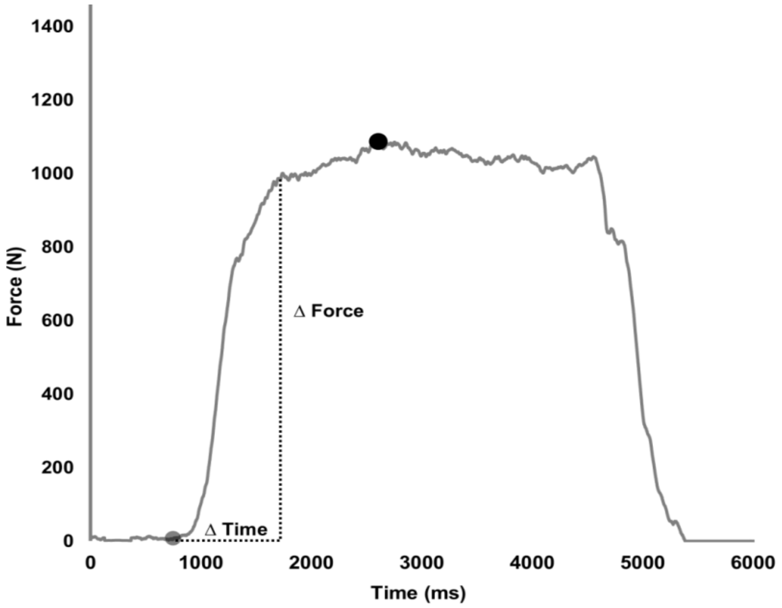

Figure 7 – Sample force-time curve, with data sampled at 1 kHz. Dark grey circle indicates the start of the contraction, black circle indicates the point at which the peak force value was achieved, Δ force = change in force (N), Δ time = change in time (ms). Note that in this example, peak force does not include the subject's body weight.

2.2.6 Isometric squat contraction exclusion criteria

The most common reason for excluding an ISq trial is the presence of a countermovement at the initiation of the contraction (Chavda *et al*. 2020). This becomes visible on inspection of the force-time curve (see Figure 8 below). To author's knowledge, there is no established threshold force level that constitutes a countermovement during isometric strength testing. However, Comfort *et al.* (2019) recommend rejecting trials if force changes by > 50 N during the quiet standing period immediately prior to contraction initiation, which could be extended to include countermovements. Besides the fact that a countermovement invalidates the “isometric” nature of the contraction, it more often than not leads to an inflated PIF compared to what would have been achieved if the contraction was performed without a countermovement. A visual representation of this exact phenomenon is shown in Figure 8.

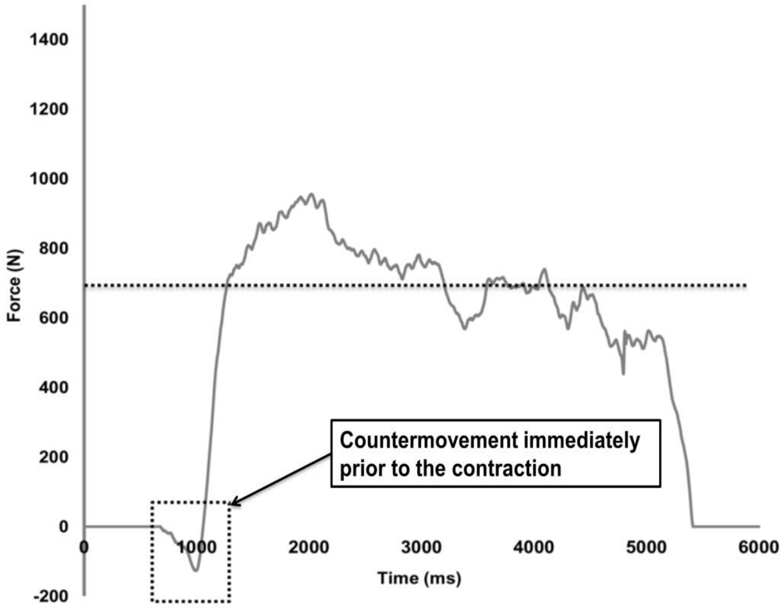

Figure 8 – Example force-time curve highlighting a countermovement immediately prior to the maximal effort ISq contraction.

In addition to excluding trials due to the presence of a countermovement, trials were excluded if the baseline period (the time period immediately prior to contraction onset) was not stable, with < 50 N fluctuation during this period deemed acceptable for the isometric mid-thigh pull (Comfort *et al.* 2019). This is represented with an example in Figure 9. Additionally, Comfort *et al.* (2019) suggest that trials should be excluded if the PIF occurs at the end of the contraction, though an exact time-point within the contraction for this has not been established and it is left to the discretion of the investigator. An example of this pattern is shown in Figure 10. Finally, trials were excluded if a countermovement occurred during the contraction, which is problematic as it can also lead to an inflated PIF value. An example of this is displayed in Figure 11.

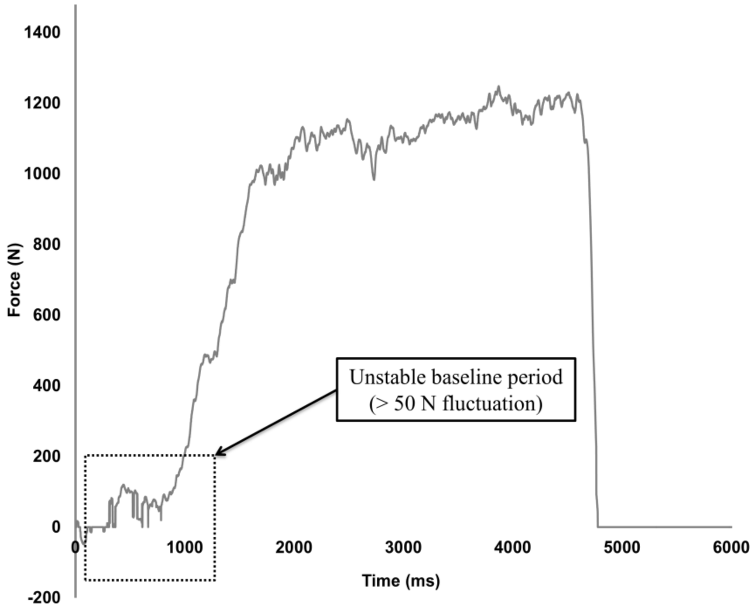

Figure 9 – Example force-time curve with an unstable baseline period. A fluctuation of up to 50 N is considered acceptable for the isometric mid-thigh pull (Comfort *et al*. 2019).

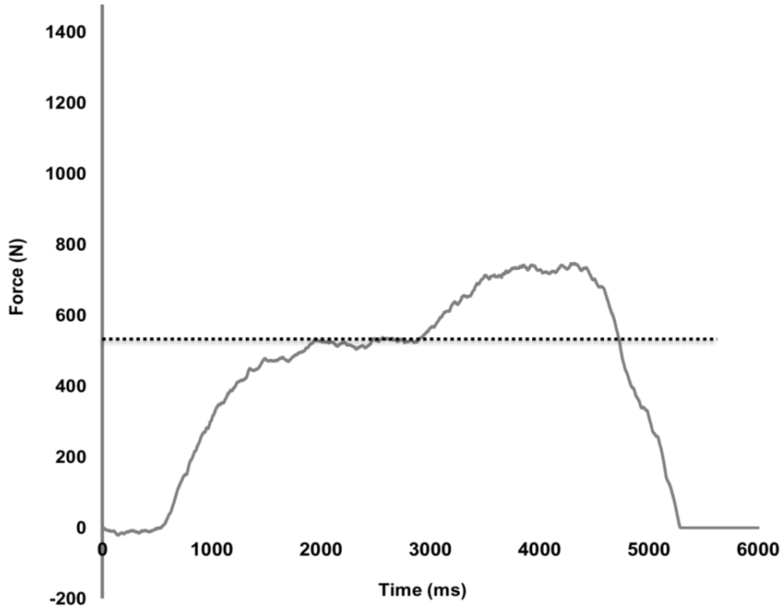

Figure 10 – Example force-time curve where the peak force occurs at the end of the contraction, as indicated by the dashed line.

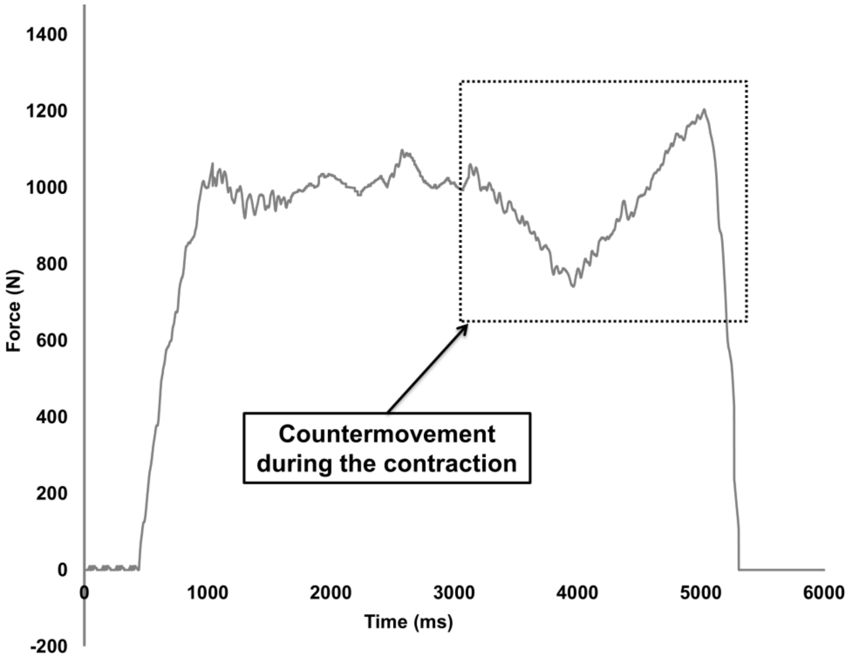

Figure 11 – Example force time-curve with a countermovement occurring during the contraction. Note how this leads to an inflated peak isometric force.

To summarize, the criteria for exclusion of an isometric squat contraction were as follows:

1. Presence of a countermovement immediately prior to the onset of the contraction.
2. Unstable baseline period immediately prior to the onset of the contraction, defined as exceeding a 50 N fluctuation during this period (Comfort *et al*. 2019).
3. Peak force obtained at the end of the contraction.
4. Presence of a countermovement during the contraction.

2.3 One repetition maximum back squat

2.3.1 Apparatus

All one repetition maximum (1 RM) back squat testing was conducted using a Powerlifting competition combo rack (ER Equipment, Denmark), a 20 kg calibrated Powerlifting barbell (Rogue, Ohio) and standard barbell plates (York Barbell, Pennsylvania).

2.3.2 General performance procedures and criteria for the back squat

The procedure for the 1RM test was guided by the criteria outlined in the rulebook of the International Powerlifting Federation (IPF, 2020). The procedure for completing back squat attempts was as follows:

1. The subject faced the rack when performing the squat attempt. The bar was held horizontally across the shoulders, with the hands and fingers gripping the bar at all times.

2. After un-racking the bar, the subject walked backwards to establish the start position. Once the position was established the subject began the squat by flexing at the hips, knees and ankles until the top surface of the thigh at the hip joint was lower than the top of the knee (see Figure 12).
3. The subject ascended back to the upright position with the hips and knees extended.
4. Double bouncing at the bottom of the squat attempt or any downward movement on the concentric phase of the lift was not permitted.
5. A spotter was present at all times at each end of the barbell, with a third investigator judging the bottom position of the range of motion (herein referred to as "depth") and any downward movement of the barbell that may have occurred during the concentric phase of the lift.

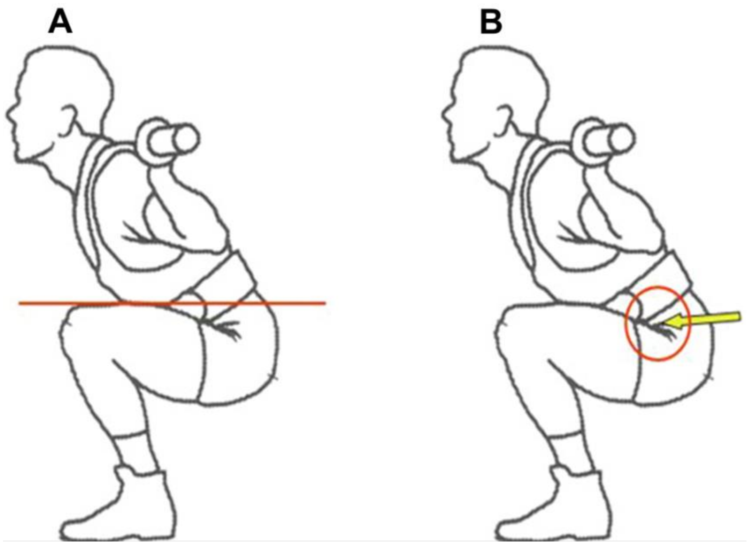

Figure 12 – Required squat depth for an acceptable 1RM attempt. The criterion for acceptable squat depth states that the top of the thigh at the hip must be below the top of the knee, which is depicted by the red line in **A** and again by the arrow in **B** (IPF, 2020).

2.3.3 Warm up procedure for sub-maximal attempts

As all 1RM testing was conducted after ISq testing, the subjects were already prepared for the 1RM test. However, if subjects requested it then they were allowed to perform any dynamic stretches (e.g. bodyweight squats) they wished prior to commencing the 1RM test. In the case of a subject performing their initial 1RM on the very first test day, the estimated 1RM value provided in their informed consent and subject information sheet was used to guide the sub-maximal (or warm up) attempts. For subsequent 1RM tests, the previous 1RM value was used as the estimated 1RM. The warm up procedure was conducted in accordance with the guidelines of Baechle and Earle (2008):

1. The subject warmed up with a light resistance that easily allowed for 5 to 10 repetitions (typically the empty 20 kg barbell).
2. A 1 minute rest period was provided.
3. A warm-up load that allowed the subject to comfortably complete three to five repetitions was estimated by adding 15-20 kg or 10 % to 20 % of the estimated 1RM.
4. Steps 2 and 3 were repeated (using only single repetitions for each set once the load was ≥ 70 % of estimated 1RM) until the subject completed 90 % of the estimated 1RM.

2.3.4 Maximal attempt procedures

Following completion of the 90 % of estimated 1RM load, the subject provided a rating of perceived exertion (RPE) using the 1-10 scale from Zourdos *et al*. (2015), which is shown in Table 3. The barbell load was progressively increased by 1-5 kg until the 1RM was achieved, with a 3 minute rest period provided between each attempt. The subject provided an RPE after each attempt ≥ 90 % of estimated 1RM. The increments were selected based on the RPE provided by the subject as follows:

(i) RPE < 7 = 10 kg increment
(ii) RPE 7-7.5 = 5 kg increment
(iii)RPE 8-9 = 2.5 kg increment
(iv) RPE 9.5 = 1 kg increment

Rating	Description of perceived effort
10	Maximum effort
9.5	No further repetitions but could increase load
9	1 repetition remaining
8.5	1-2 repetitions remaining
8	2 repetitions remaining
7.5	2-3 repetitions remaining
7	3 repetitions remaining
5-6	4-6 repetitions remaining
3-4	Light effort
1-2	Little to no effort

Table 3 - Resistance exercise specific rating of perceived exertion (RPE) scale (taken from Zourdos *et al.* 2015).

2.3.5 Criteria for an acceptable 1RM

The maximal attempt procedure was repeated until the actual 1RM was achieved. If the subject reported an RPE of 10 on any attempt, then the test was ended. If the subject failed to stand up with an attempt, then the most recent successful attempt was taken as the 1RM. In addition, the following were considered grounds for failure in the 1RM:

1. Not achieving the required squat depth (see Figure 12)

2. Inability to stand up with the load

3. Receiving assistance from the spotters

4. An unacceptable amount of technique deterioration (e.g. a substantial change in the degree of spinal flexion exhibited by a subject from one attempt to the next). If this occurred then the test was ended in the interests of subject safety and the most recent attempt was taken as the 1RM.

Chapter 3

3.0 The influence of squat position on the reliability of isometric squat force variables

Preface

Previous investigations of the ISq have not explored the utility of positions that stipulate a knee angle of < 90°. Given that many investigations have attempted to correlate PIF in the ISq with 1RM back squat weight lifted (Bazyler *et al*. 2015; Drake *et al*. 2018), it is curious that ISq positions with a knee angle of < 90° have not been previously investigated. Perhaps this may be due to inferior reliability and/or substantially lower PIF compared to more well-established ISq positions that are performed at knee angles of ≥ 90°. Therefore the aim of this study was to examine the overall utility of an ISq test performed at three different positions including an ISq at a 65° knee angle, a previously unexplored position.

3.1 Abstract

The purpose of this investigation was to report the within- and between-day reliability of peak isometric force (PIF) and rate of force development (RFD) in an isometric squat (ISq) test in three distinct squatting positions. A secondary objective of the study was to compare the magnitude of PIF and RFD values across the three ISq positions. On two separate days, 17 healthy recreationally active men aged 18 to 35 years performed three maximal

effort ISq contractions at a 120° (ISq$_{120}$), 90° (ISq$_{90}$) and 65° (ISq$_{65}$) knee angle (180° = full knee extension). Reliability was determined from the coefficient of variation (CV) and intraclass correlation coefficient (ICC), using established reliability thresholds ($<$ 10 % CV, $\geq$ 0.8 ICC). Typical error (TE) for each position was also calculated. PIF was greater in ISq$_{120}$ (mean (SD); 1259 (525) N) than in ISq$_{90}$ (919 (287) N) and ISq$_{65}$ (820 (205) N) ($P < 0.001$). There were no differences in RFD (0-250 ms) between days or positions (ISq$_{120}$ 2817 (1282) N·s^{-1}, ISq$_{90}$ 2948 (1003) N·s^{-1}, ISq$_{65}$ 2680 (1017) N·s^{-1}) with the exception of ISq$_{120}$, which was significantly greater than ISq$_{65}$ on day 2 ($P = 0.01$). Based on the ICC scores for PIF, ISq$_{120}$ was the most reliable position (ICC [95 % CI]; ISq$_{120}$ = 0.969 [0.914, 0.989], ISq$_{90}$ = 0.892 [0.702, 0.961], ISq$_{65}$ = 0.916 [0.766, 0.970]). Differences in measurement reliability for PIF based on CV were negligible ($P > 0.44$) between positions (ISq$_{120}$ CV = 7-10 %, ISq$_{90}$ CV = 9-12 %, ISq$_{65}$ CV = 8-11 %). There were no differences in measurement reliability between positions for RFD based on ICC (ISQ$_{120}$ = 0.833 [0.552, 0.939], ISQ$_{90}$ = 0.782 [0.418, 0.920], ISq$_{65}$ = 0.881 [0.679, 0.956]) or CV (ISq$_{120}$ CV = 13-18 %, ISq$_{90}$ CV = 9-13 %, ISq$_{65}$ CV = 8-14 %, $P > 0.21$). RFD data were deemed to not be of acceptable reliability based on CV values, exceeding the recommended $<$ 10 % threshold. Finally, TE values of 118.3 N, 116.5 N and 83.2 N were determined for ISq$_{120}$, ISq$_{90}$ and ISq$_{65}$ PIF respectively. It is concluded that compared to ISq$_{90}$ and ISq$_{65}$, the ISq$_{120}$ position facilitates greater force production and appears to demonstrate equivalent, if not greater test reliability.

3.2 Introduction

One of the characteristics of effective measurement outlined in the introductory Chapter is reliability, which refers to the degree to which the measurement produces the same value when repeated in the same subject or specimen under the same conditions (Lachin 2004). Assuming the test measures what it intends to measure (i.e. validity); reliability is arguably the next most important measurement characteristic. Additionally, the reliability of a test can also indicate its sensitivity as a more reliable test is associated with lower measurement error and therefore is capable of detecting smaller changes over time (Hopkins 2000; Currell and Jeukendrup 2008). Conversely, a measure that has poor test-retest reliability necessitates greater change over time in order to be considered real (i.e. outside the range of error typically associated with the measure).

Whilst a variety of ISq tests have been shown to provide accurate and reliable data, no standardised position has been adopted or recommended (Bazyler *et al.* 2015; Blazevich *et al.* 2002; Drake *et al*. 2018). This is in contrast with the isometric mid-thigh pull, which has a standardised test position (Beckham *et al.* 2018; Comfort *et al.* 2019). A number of previous studies have documented the reliability of a variety of ISq tests and positions. Whilst most of these studies have only looked at one position, some have compared ISq reliability across different positions (see Table 4 for a summary of these studies).

Author	Subjects	Knee angle/s	CV	ICC
Tillin *et al.* (2013)	18 trained male athletes	120°	4.0	0.96
Blazevich *et al.* (2002)	12 trained males	90°	——	0.97
Bazyler *et al.* (2015)	17 trained men	90°	2.9	0.99
		120°	3.0	0.97
Brady *et al.* (2017)	16 male & 10 female trained athletes	140°	4.6	0.97
Nuzzo *et al.* (2008)	12 male athletes	140°	——	≥ 0.98
Hart *et al.* (2012)	11 trained men	140°	3.6	0.97
Lum & Joseph (2019)	18 male & 6 female trained athletes	90°	——	0.99
		120°	——	0.98
Palmer *et al.* (2017)	14 trained females	90°	12.0	0.840
		120°	11.2	0.839
		150°	6.6	0.904
Drake *et al.* (2018)	42 trained males	90°	3.9	0.885

Table 4 – Summary of reliability data for peak force in the isometric squat. CV = coefficient of variation, ICC = intraclass correlation coefficient.

Two commonly used ISq positions place the subject at a knee angle of 120° or 90° (Bazyler *et al.* 2014; Bazyler *et al.* 2015; Blazevich *et al.* 2002; Drake *et al.* 2018; Marcora and Miller 2000; Nuzzo *et al.* 2008; Palmer *et al.* 2017). The 120° knee angle position closely replicates the strongest position of the back squat (McLaughlin *et al.* 1977), whereas the 90° knee angle approximates the ‘sticking point’ of the back squat (*i.e.* the point at which momentary muscular failure occurs during the lift), which correlates well with dynamic 1RM performance (Bazyler *et al*. 2015; Blazevich *et al.* 2002; Kompf and Arandjelović 2017). Assessment of strength at both a 120° and/or 90° knee angle may also be appealing in an untrained cohort as there is minimal skill and mobility required to perform the ISq in these positions.

According to Brady *et al*. (2018), previous ISq investigations have not explored the reliability of ISq positions that are conducted at a knee angle of < 90°. To the author's knowledge, this is still the case and is represented visually in Figure 13. Reasons for this may include difficulty attaining the position, substantially lower peak forces compared to higher ISq positions and potentially lower reliability, given that some previous evidence has shown a tendency for ISq reliability to decrease as the knee angle moves further away from extension (Palmer *et al.* 2017). However, it could be argued that an ISq assessment that is conducted in a deep squatting position (i.e. < 90°) may be safer in untrained populations who are not familiar with these positions, compared to typical isoinertial assessments of lower body strength that demand the same range of motion (e.g. a full range of motion 1RM back squat). Additionally, assessment of strength in deep squat positions may be of relevance to athletes, particularly those involved in strength sports like Powerlifting and Olympic weightlifting who squat to much lower depths than 90° and 120° knee angles (Glassbrook *et al.* 2017). Therefore this study sought to compare the reliability of ISq measurement in a previously unexplored deep squat position, requiring subjects to perform maximal effort ISq contractions at a 65° knee angle, compared to more established ISq positions (90° and 120° respectively). A 65° knee angle position approximates the criteria for full depth in the back squat exercise (Hales *et al.* 2009; IPF 2019; McLaughlin *et al.* 1977; Swinton *et al.* 2012).

As previously indicated, the reliability of ISq assessment at a 65° knee angle is currently unknown (Table 4, Figure 13).

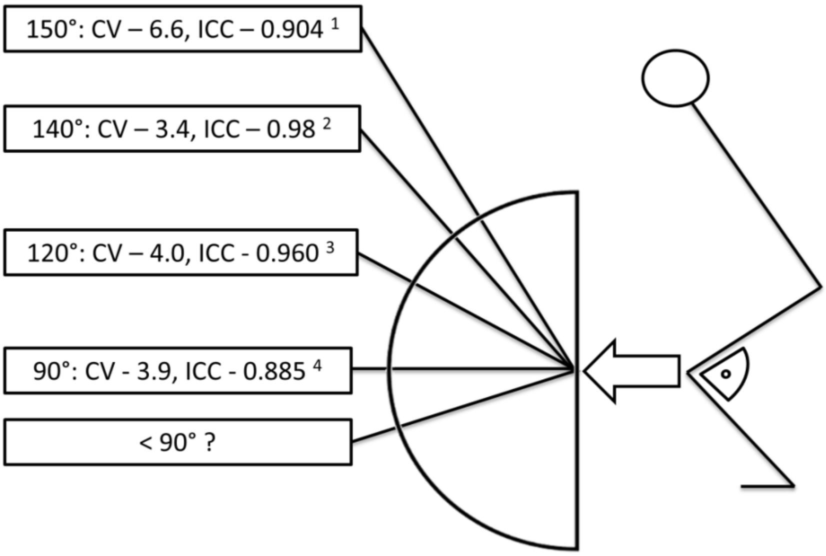

Figure 13 – Visual representation of reliability data reported for peak force in the isometric squat across different knee angles. ^{1} – Palmer *et al.* (2017), ^{2} – Hart *et al.* (2012), ^{3} – Tillin *et al.* (2013), ^{4} – Drake *et al.* (2018).

The purpose of this investigation was to analyse the effect of ISq position on the reliability of force measurement in the ISq, using three distinct squat positions (120°, 90° and 65° knee angle). A secondary objective of the study was to compare the PIF as well as RFD between the three positions. It was hypothesised that both force output and reliability would be greater as the knee angle moved closer to full extension (*i.e.* 120° > 90° > 65°).

3.3 Methods

3.3.1 Design overview

Using a single-group repeated measures design the effect of ISq position on inter- and intraday reliability for MF (N), PIF (N) and allometrically scaled PIF ($N/Kg^{0.67}$) as well as RFD ($N \cdot s^{-1}$). All subjects performed three maximal effort ISq in the three different squat positions on two non-consecutive test days, separated by at least 72 h (range: 72 to 168 h).

3.3.2 Subjects

The study design, documentation and procedures were approved by the University of Limerick Education and Health Sciences Research Ethics Committee, in accordance with the declaration of Helsinki (ethical approval number EHS_2016_12_09). Prior to inclusion subjects were informed of the benefits and risks of participation before giving written informed consent. Eligibility criteria were: (i) men, (ii) 18 to 35 years of age, (iii) habitually active and in good general health with no current injuries, illness or history of disease. In total, 17 male subjects (mean (SD) age 22.7 (2.7) years, body mass 81.6 (11.1) kg, height 1.78 (7.1) m) were recruited from the locality and voluntarily participated in the study.

3.3.3 Procedures

The procedures for the isometric squat testing are outlined in depth in 2.2 of Chapter 2. ISq testing was conducted at a 120°, 90° and 65° knee angle, as outlined in that section.

Subjects reported to the lab each test day at the same time each day (10:00 to 14:00). Eligibility and familiarisation with the test procedures was undertaken 24 to 72 h prior to starting the study. Subjects were instructed to maintain their normal eating habits throughout the study. Dietary intake was recorded prior to the first test day and each subject was instructed to repeat this intake before the second test day. This was verified via dietary records by a qualified dietician. In addition, subjects were instructed to refrain from any formal lower body exercise 48 h prior to testing.

ISq force variables were measured in a custom made squat rack with a fixed barbell, adjustable in height, positioned above a force plate (AMTI, Watertown MA) and bolted to the floor (see Figure 5 of Chapter 2). The three positions were set as: (i) 120° knee angle (ISq_{120}); (ii) 90° knee angle (ISq_{90}) and (iii) 65° knee angle (ISq_{65}), where the greater trochanter is below the level of the superior border of the patella (180° = full knee extension). The ISq_{65} position approximates the knee angle observed in the bottom position of the back squat in powerlifting under maximal loads (Hales *et al.* 2009; Swinton *et al.* 2012) and is considered the criteria for full squat depth by the International Powerlifting Federation (IPF 2020).

During the setup, subjects were allowed to self-select their stance width and foot position, this was then measured, recorded and marked with tape to ensure consistency between trials and days. Subjects followed the same sequence each test day (ISq_{65}, ISq_{90} and then ISq_{120}), completing three warm up ISq in the first position prior to measurement (50 %, 70 % and 90 % of perceived maximal effort) which were maintained for at least 3 s with 1 min rest between each ISq (Beckham *et al.* 2018). For each maximal effort ISq subjects were given standard verbal encouragement from the investigators, who instructed subjects to “push as hard and fast as possible into the bar” and to maintain peak force output for the duration of the contraction. At the onset of the audible cue the contraction started and subjects were encouraged by the experimenters to maintain a 3 s contraction. Three maximal effort ISq contractions were performed in each squat position, with 3 min rest given between each attempt to minimize fatigue accumulation (Willardson 2006).

Ground reaction force data were sampled at 1 kHz and excluded if any countermovement was evident. PIF was reported as the peak force generated minus the subject's body weight, whereas MF was reported as the peak force inclusive of subject body weight (Brady *et al*. 2017) and in both cases this was the highest value attained out of the three attempts. Allometrically scaled PIF ($N/kg^{0.67}$) was calculated by dividing the PIF by body mass raised to the 0.67 power (Folland *et al*. 2008; Brady *et al*. 2017). RFD was derived from the force-time curve (ΔForce/ΔTime) using the 0-250ms time band (relative to the onset of the contraction). As outlined in Chapter 2, the ISq testing procedures employed in this thesis were not preferable for obtaining valid and reliable RFD data (Drake *et al*. 2019), as PIF was considered to be of greater importance. However, it was chosen to provide these data in order to document the reliability of RFD under these testing conditions. In addition, larger time bands (e.g. 0-200ms, 0-250ms) have previously been shown to provide more reliable data compared to shorter (e.g. 0-50ms, 0-100ms etc.) time bands (Brady *et al*. 2017; Palmer *et al*. 2017; Maffiuletti *et al*. 2016).

3.3.4 Statistical Analyses

Within-day (day 1 *and* day 2) and between-day (day 1 *vs.* day 2) reliability scores were calculated for MF, PIF and allometrically scaled PIF as well as RFD. Normality and homogeneity of variance were assessed prior to analysis, using a Shapiro-Wilk and Levene's test respectively. In addition, skewness and kurtosis was assessed prior to analysis. A two-way random model with absolute agreement was used to calculate the intra-class correlation coefficient (ICC) (Koo and Li 2016). The ICC is the most commonly employed statistic used in ISq reliability studies (Bazyler *et al.* 2015; Blazevich *et al.* 2002; Brady *et al.* 2017; Drake *et al.* 2018; Nuzzo *et al.* 2019; Palmer *et al.* 2017), which allows for comparison across reliability studies. The ICC is a unitless index of reliability between repeat trials, the closer the ICC value is to 1, the greater the agreement between trials (Nuzzo *et al.* 2019). An ICC over 0.9 was defined as highly reliable, between 0.8 and 0.9 as moderately reliable, and below 0.8 as not reliable (Atkinson and Nevill 1998; Bland and Altman 1990).

Inter- and intra-day coefficient of variation (CV) was also calculated. The CV is an appealing statistic to use for comparison purposes, largely due to its dimensionless nature, allowing direct comparison across measures regardless of their unit of measurement (provided they are on a ratio scale) (Hopkins 2000). CV also facilitates comparison across different analysers, tests or populations of volunteers (Hopkins 2000) and this was calculated by dividing the standard deviation by the mean, multiplied by 100 (Atkinson and Nevill 1998). Within and between-day change with upper and lower (95 %) levels of agreement (LOA) were used to assess systematic bias. Paired samples t-tests were used to assess differences within and between days and between positions, with the alpha level set at $P < 0.05$. Effect size (d) was calculated for differences in MF, PIF, allometrically scaled PIF and RFD between positions by dividing the position difference by the pooled standard deviation (Cohen 1988). The magnitudes of these effect sizes were classified as small (0.2), medium (0.5) or large (0.8) (Cohen 1988). Finally, typical error (TE) was calculated for PIF, allometrically scaled PIF and RFD respectively by dividing the standard deviation of the within-subject differences between the two test days (i.e. the peak of day 1 and the peak of day 2) by $\sqrt{2}$ (Hopkins 2000; Swinton *et al*. 2018). TE was not calculated for MF. Given that this variable is influenced by subject body weight, PIF would appear to be the more appropriate variable to assess chronically. TE provides an indication of the change score required between trials in order to be considered “real” (i.e. outside the normal range of error associated with the test) (Hopkins 2000). As such, the TE could be considered an index of the sensitivity of the measure to detect change over time and provides real value for practitioners who may consider using the ISq to measure performance changes in response to a training program (Drake et al. 2018; Hopkins 2000).

3.4 Results

Maximum force, peak isometric force and allometrically scaled peak isometric force

The reliability of MF, PIF and allometrically scaled PIF are presented in Tables 5, 6 and 7 respectively. The greatest force was observed in the ISq_{120} position compared to ISq_{90} and ISq_{65} (ISq_{120} vs. ISq_{90}, $P < 0.001$, $d \geq 0.8$; ISq_{120} vs. ISq_{65}, $P < 0.001$, $d \geq 1.0$). Differences between the ISq_{90} and ISq_{65} positions were not as pronounced ($P \leq 0.57$, $d \geq 0.1$). No differences in measurement reliability were observed based on ICC values for MF, PIF and allometrically scaled PIF at ISq_{120} (range = 0.940-0.976) compared to ISq_{90} (range = 0.852-0.965) or ISq_{65} (range = 0.827-0.967). In addition, based on CV values (ISq_{120} CV = 5-10 %, ISq_{90} CV = 5-12 %, ISq_{65} CV = 4-

11 %) differences in measurement reliability between positions were not significant ($P \geq 0.08$). Mean between-day difference (Day 2 – Day 1) was determined via Bland Altman analysis for PIF and allometrically scaled PIF (Figure 14). No systematic bias was observed between test days for any variable or position (Figure 14). Additionally, there was no evidence of an order effect indicating potentiation or fatigue across trials. Finally, the TE values were determined for PIF (ISq_{120} = 118 N, ISq_{90} = 117 N, ISq_{65} = 83 N) and allometrically scaled PIF (ISq_{120} = 7.4 $N/kg^{0.67}$, ISq_{90} = 8.4 $N/kg^{0.67}$, ISq_{65} = 4.8 $N/kg^{0.67}$) and these are presented in Tables 6 and 7 respectively.

Rate of fore development

The reliability data for RFD ($N \cdot s^{-1}$) are presented in Table 8. No significant differences in RFD were observed between days or positions ($P \geq 0.08$, $d \leq 0.3$), with the exception of RFD at ISq_{120} on day 2, which was significantly greater than ISq_{65} on day 2 ($P = 0.010$, $d = 0.4$). With the exception of the between day reliability at ISq_{90}, mean ICC results suggest acceptable reliability (ICC > 0.8) for RFD, though the 95% confidence intervals indicate high variability around these mean values (Table 8), particularly when compared with the ICC values for MF (Table 5) and PIF (Table 6). Based on CV values, the RFD data did not achieve the acceptable reliability threshold of < 10 % CV (CV range 8-18 %). TE values revealed the change scores required over time to be considered real (ISq_{120} = 602 $N \cdot s^{-1}$, ISq_{90} = 463 $N \cdot s^{-1}$, ISq_{65} = 374 $N \cdot s^{-1}$) and these are also presented in Table 8. Mean between-day difference (Day 2 – Day 1) was determined via Bland Altman analysis for RFD and this is displayed in Figure 15. Overall, in contrast with PIF variables, the results do not demonstrate acceptable levels of reliability for RFD. This finding is unsurprising given the testing procedures employed (see Chapter 2, section 2.2.4).

Maximum force

	Day 1 (N) Mean (SD)	**Day 2 (N) Mean (SD)**	**Difference Day 2 – Day 1 (N) Mean [LLOA, ULOA]**
ISq$_{120}$	2062 (565) $_{a, b}$	2000 (520) $_{a, b}$	- 62 [-142, 17]
ISq$_{90}$	1722 (347) $_{b, c}$	1652 (344) $_{b, c}$	- 23 [-98, 51]
ISq$_{65}$	1623 (266) $_{a, c}$	1629 (295) $_{a, c}$	- 6 [-53, 66]

Within-Day Reliability

	CV [Mean (SD)]		**ICC [95 % CI]**	
	Day 1	**Day 2**	**Day 1**	**Day 2**
ISq$_{120}$	5 (3)	6 (4)	0.976 [0.941, 0.991]	0.971 [0.932, 0.989]
ISq$_{90}$	5 (3)	6 (3)	0.948 [0.870, 0.983]	0.929 [0.816, 0.978]
ISq$_{65}$	5 (3)	5 (2)	0.967 [0.910, 0.990]	0.956 [0.917, 0.988]

Between-Day Reliability

	CV [Mean (SD)]	**ICC [95 % CI]**
ISq$_{120}$	4 (4)	0.974 [0.927, 0.991]
ISq$_{90}$	6 (6)	0.933 [0.810, 0.976]
ISq$_{65}$	5 (4)	0.950 [0.863, 0.982]

Table 5 – Reliability of maximum force in the ISq. CV = Coefficent of variation, LLOA = Lower limits of agreement, ULOA = Upper limits of agreement, ICC = Intraclass correlation coefficient, 95% CI = 95% confidence interval, $_{a}$ denotes significantly different ($P < 0.05$) from ISq$_{90}$, $_{b}$ denotes significantly different from ISq$_{65}$, $_{c}$ denotes significantly different from ISq$_{120.}$

Peak isometric force

	Day 1 (N) Mean (SD)	Day 2 (N) Mean (SD)	Difference Day 2 – Day 1 (N) Mean [LLOA, ULOA]
ISq$_{120}$	1259 (525) $_{a, b}$	1197 (467) $_{a, b}$	- 63 [-142, 17]
ISq$_{90}$	919 (287) $_{c, b}$	848 (288) $_{c}$	- 23 [-98, 51]
ISq$_{65}$	820 (205) $_{c, a}$	826 (233) $_{c}$	- 6 [-53, 66]

Within-Day Reliability

	CV [Mean (SD)]		ICC [95 % CI]	
	Day 1	**Day 2**	**Day 1**	**Day 2**
ISq$_{120}$	10 (7)	10 (6)	0.940 [0.861, 0.978]	0.962 [0.913, 0.986]
ISq$_{90}$	11 (7)	12 (6)	0.932 [0.838, 0.975]	0.950 [0.863, 0.982]
ISq$_{65}$	11 (8)	11 (5)	0.827 [0.572, 0.942]	0.942 [0.858, 0.978]

Between-Day Reliability

	CV [Mean (SD)]	ICC [95 % CI]	TE (N)	TE (%)
ISq$_{120}$	7 (8)	0.969 [0.914, 0.989]	118	10.5
ISq$_{90}$	9 (11)	0.892 [0.702, 0.961]	117	14.2
ISq$_{65}$	10 (10)	0.916 [0.766, 0.970]	83	11.0

Table 6 – Reliability of peak isometric force in the ISq. CV = Coefficent of variation, LLOA = Lower limits of agreement, ULOA = Upper limits of agreement, ICC = Intraclass correlation coefficient, 95% CI = 95% confidence interval, TE = typical error, $_{a}$ denotes significantly different ($P < 0.05$) from ISq$_{90}$, $_{b}$ denotes significantly different from ISq$_{65}$, $_{c}$ denotes significantly different from ISq$_{120.}$

Allometrically scaled peak isometric force

	Day 1 **(N/kg$^{0.67}$)** **Mean (SD)**	**Day 2** **(N/kg$^{0.67}$)** **Mean (SD)**	**Difference** **Day 2 – Day 1 (N/kg$^{0.67}$)** **Mean [LLOA, ULOA]**
ISq$_{120}$	116.2 (34.5) $_{a, b}$	116.1 (34.8) $_{a, b}$	-5.0 [-10.0, 0]
ISq$_{90}$	91.2 (18.5) $_{b, c}$	94.2 (22.0) $_{c}$	-4.8 [-10.5, 0.8]
ISq$_{65}$	83.2 (17.5) $_{a, c}$	81.9 (17.4) $_{a, c}$	0.2 [-3.0, 3.5]

Within-Day Reliability

	CV [Mean (SD)]		**ICC [95% CI]**	
	Day 1	**Day 2**	**Day 1**	**Day 2**
ISq$_{120}$	10 (7)	9 (7)	0.959 [0.899, 0.985]	0.963 [0.908, 0.988]
ISq$_{90}$	9 (6)	12 (6)	0.965 [0.905, 0.990]	0.852 [0.611, 0.954]
ISq$_{65}$	9 (6)	10 (4)	0.914 [0.741, 0.979]	0.953 [0.884, 0.983]

Between-Day Reliability

	CV [Mean (SD)]	**ICC [95% CI]**	**TE (N/kg$^{0.67}$)**	**TE (%)**
ISq$_{120}$	6 (5)	0.948 [0.846, 0.982]	7.4	12.6
ISq$_{90}$	10 (8)	0.921 [0.779, 0.972]	8.4	19.6
ISq$_{65}$	10 (9)	0.902 [0.728, 0.965]	4.8	12.1

Table 7 – Reliability of allometrically scaled peak isometric force in the ISq. CV = Coefficent of variation, LLOA = Lower limits of agreement, ULOA = Upper limits of agreement, ICC = Intraclass correlation coefficient, 95% CI = 95% confidence interval, TE = typical error, $_{a}$ denotes significantly different ($P < 0.05$) from ISq$_{90}$, $_{b}$ denotes significantly different from ISq$_{65}$, $_{c}$ denotes significantly different from ISq$_{120}$.

Rate of force development

	Day 1 (N·s^{-1}) Mean (SD)	Day 2 (N·s^{-1}) Mean (SD)	Difference Day 2 – Day 1 (N·s^{-1}) Mean [LLOA, ULOA]
ISq$_{120}$	2817 (1187)	2506 (121) ^{a}	-311 [-748, 127]
ISq$_{90}$	2548 (802)	2354 (761)	-194 [-530, 144]
ISq$_{65}$	2102 (745)	2040 (673) ^{b}	-173 [-446, 99]

Within-Day Reliability

	CV [Mean (SD)]		ICC [95 % CI]	
	Day 1	Day 2	Day 1	Day 2
ISq$_{120}$	14 (8)	13 (10)	0.859 [0.641, 0.953]	0.947 [0.819, 0.989]
ISq$_{90}$	13 (6)	9 (7)	0.924 [0.778, 0.980]	0.871 [0.251, 0.991]
ISq$_{65}$	14 (9)	8 (5)	0.907 [0.752, 0.971]	0.886 [0.595, 0.979]

Between-day reliability

	CV [Mean (SD)]	ICC [95 % CI]	TE (N·s^{-1})	TE (%)
ISq$_{120}$	18 (12)	0.833 [0.552, 0.939]	602	24.9
ISq$_{90}$	13 (13)	0.782 [0.418, 0.920]	463	20.1
ISq$_{65}$	14 (10)	0.881 [0.679, 0.956]	375	17.3

Table 8 – Reliability of rate of force development in the ISq (0-250ms time band). CV = Coefficent of variation, LLOA = Lower limits of agreement, ULOA = Upper limits of agreement, ICC = Intraclass correlation coefficient, 95% CI = 95% confidence interval, TE = typical error, $_a$ denotes significantly different ($P < 0.05$) from ISq$_{65}$, $_b$ denotes significantly different ($P < 0.05$) from ISq$_{120.}$

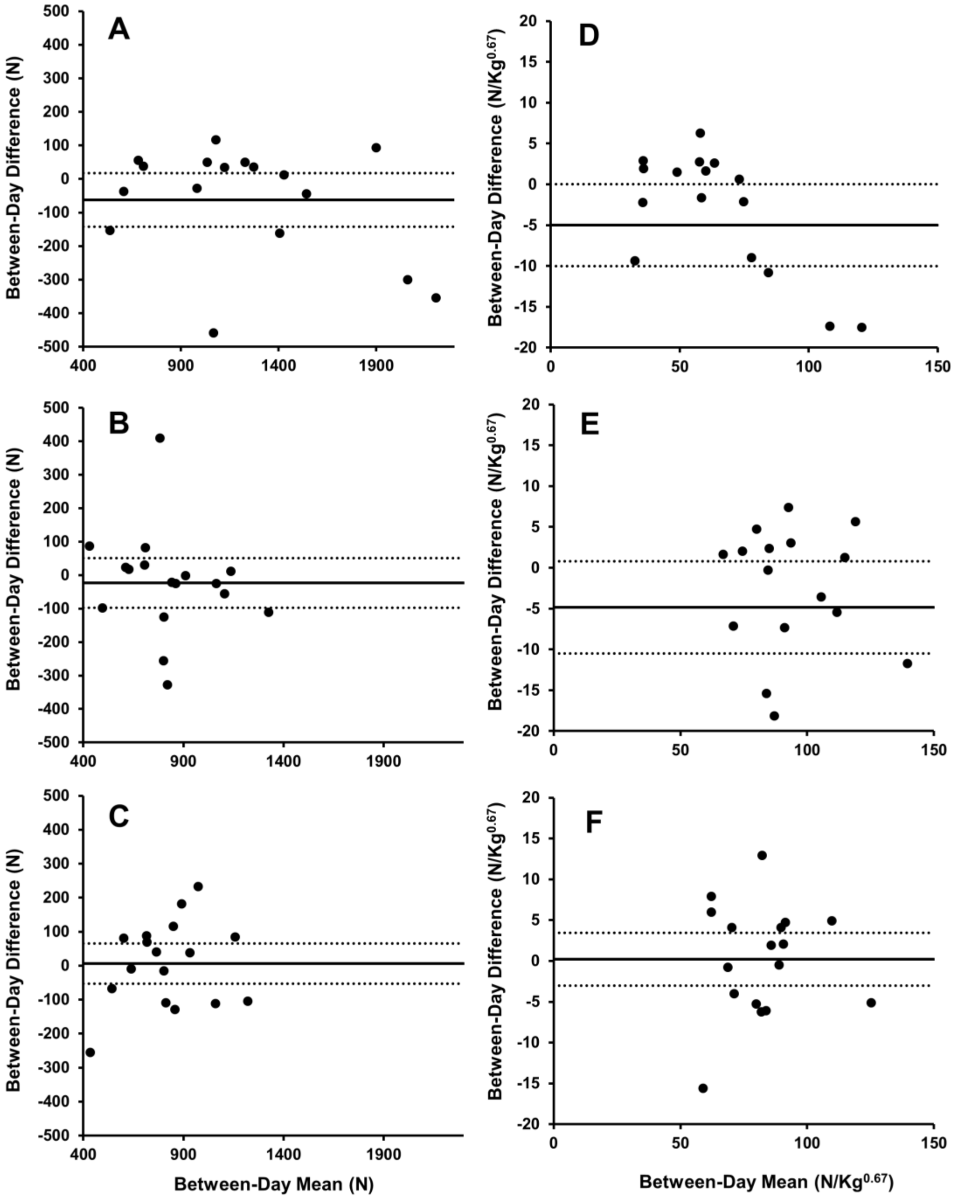

Figure 14 - Bland Altman plots for between-day peak isometric force and allometrically scaled peak isometric force: (A) PIF at ISq_{120}, (B) PIF at ISq_{90}, (C) PIF at ISq_{65}, (D) allometrically scaled PIF at ISq_{120}, (E) allometrically scaled PIF at ISq_{90}, (F) allometrically scaled PIF at ISq_{65}. Solid line represents the mean difference; dashed lines represent 95 % limits of agreement.

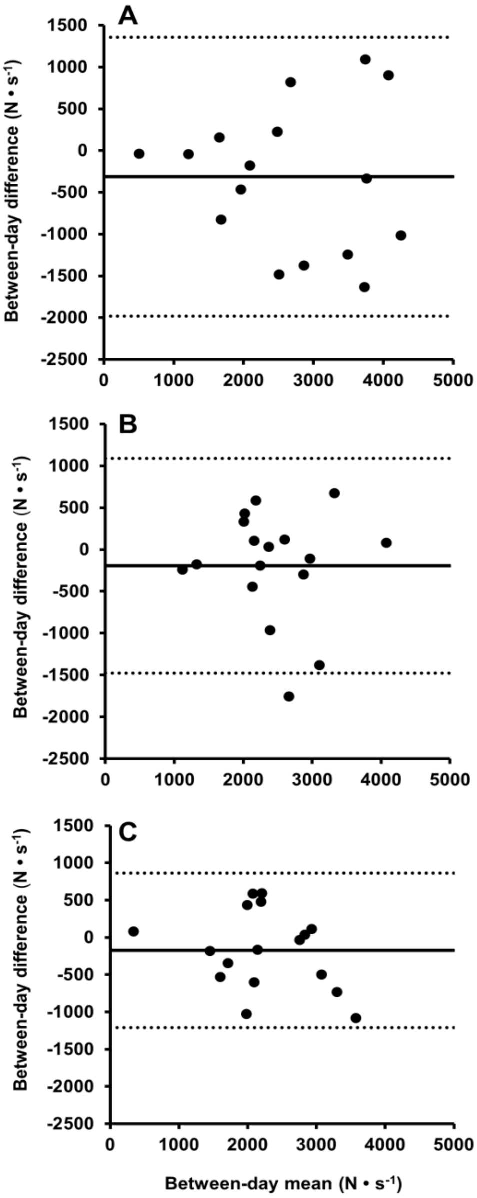

Figure 15 - Bland Altman plots for between-day rate of force development (RFD): (A) RFD at ISq_{120}, (B) RFD at ISq_{90}, (C) RFD at ISq_{65}. Solid line represents the mean difference; dashed lines represent 95 % limits of agreement.

3.5 Discussion

The objective of this study was to determine the reliability of maximum force, PIF, allometrically scaled PIF and RFD in an ISq test in three distinct ISq positions. Currently, no standardised position exists for the measure despite previous use of the ISq within the literature (Bazyler *et al.* 2015; Blazevich *et al.* 2002; Drake *et al.* 2017; Drake *et al*. 2018). In addition, to the best of the current author’s knowledge, this is the first study to investigate the use of an ISq position that requires a 65° knee angle. This position approximates the bottom position of the back squat exercise (Hales *et al*. 2009; Swinton *et al.* 2012).

Our analysis of reliability was determined using the reliability statistics CV and ICC as well as the LOA via Bland Altman analysis (Tables 5, 6, 7 and 8; Figures 14 and 15). These statistics are covered in greater detail elsewhere (Atkinson and Nevill 1998; Hopkins *et al.* 2000; Nuzzo *et al.* 2019; Weir 2005). In short, the CV is an appealing statistic to use in studies of reliability as it is easily comprehendible and as a dimensionless statistic, it facilitates comparison across measures, such as is the case here in the comparison of our results with that of other ISq tests, 1RM etc. (Atkinson and Nevill 1998). As a unitless index of reliability between repeat trials, the ICC allows for comparison across studies and is the most commonly used reliability statistic to use within reliability studies (Nuzzo *et al.* 2019). However, when taken on its own the ICC is not as easy to interpret as the CV and has a number of disadvantages. The ICC can be sensitive to sample heterogeneity, leading to high ICC values in the presence of high levels of measurement error (Atkinson and Nevill 1998). In a similar vein, homogeneity of the sample can produce low ICC values even if measurement error is low (Weir 2005). It is primarily for these reasons that it is recommended to use the ICC in conjunction with other statistics in reliability studies (Atkinson and Nevill 1998; Brady *et al.* 2017). In interpreting the results of the LOA, Atkinson and Nevill (1998) consider the LOA to be the expected range in which a new individual's score from the studied population would lie, with an approximate 95% probability (Atkinson and Nevill 1998). This method is used to quantify the level of agreement between two measures (or in this case the same measure performed on two separate occasions), though it cannot be used to assess whether or not the differences between two measures are significant (Giavarina 2015). The Bland Altman analysis revealed no systematic error, though a considerable amount of random error was present, particularly with regards to RFD (Figure 15). Sources of random error can include alertness, attentiveness by the tester, and normal biological variability (Weir 2005). Random error is viewed as being of greater concern than systematic error as random error is considered to be the 'noise' in the measurement (Hopkins 2000). Therefore, the greater the random error, the less reliable the measurement is. Hopkins (2000) recommend using larger sample sizes in the presence of high amounts of random error, as the random errors from each measurement tend to cancel out when more measurements are added.

As outlined in the methods section, TE values were calculated to indicate the change scores required over time to be considered real in the ISq. As it is calculated by dividing the SD of the difference scores (i.e. difference between value for Day 1 and the value for Day 2) by √2, the TE is dependent on the within-subject variation, as opposed to the between-subject variation (Hopkins 2000). Using a statistic that is dependent on the between-subject variation, such as the smallest worthwhile change, calculated by multiplying the between-subject SD by 0.2 (Hopkins 2000), would not have been appropriate to use in this sample of individuals who were recruited randomly and displayed marked heterogeneity for both PIF and RFD variables (Tables 6, 7 and 8). Another commonly used statistic in this type of analysis is the minimum difference (MD) (Weir 2005; Drake *et al*. 2018). The MD is equal to the standard error of measurement (SEM) multiplied by 1.96, multiplied by √2 (Weir 2005). Prior to this step, the SEM is calculated by multiplying the SD by √1-ICC (Weir 2005). However, available evidence suggests the MD is an overly cautious statistic that lacks overall practicality when used in this application. To illustrate this point, Weir (2005) provides an example of a hypothetical athlete with a 1RM of 146 kg, with an observed test-retest variability of 6 kg (or 4.1 %). Using data from a hypothetical (but entirely plausible) sample, Weir (2005) concludes that an MD of 21.07 kg (or 14.4 %) would be required in this example for a change score to be considered ‘real’. Statistically, this may make sense, but practically speaking it does not. Based on this interpretation, any increases in 1RM below the MD of 21.07 kg would not be considered real. Data from Palmer *et al*. (2017) provides further evidence of the same issue. MD scores of 307.9 N (a 31 % change) and 259.1 N (a 33 % change) were reported for PIF in the ISq_{120} and ISq_{90} respectively. Changes of such magnitude would be very difficult to achieve outside of untrained individuals (Sale 1988). The CV and ICC data from Palmer *et al*. (2017) are comparable with that of the current study (Tables 6 and 8 for PIF and RFD respectively), though the use of TE instead of the MD provides a required minimum change score that is more realistic for researchers and practitioners alike.

PIF data from the present study are in line with previous isometric strength testing research, with similar values reported for MF and PIF at ISq_{120} (Lum and Joseph 2019) and ISq_{90} (Newton *et al*. 2002). In addition, PIF was greatest in the ISq_{120} compared to ISq_{90} and ISq_{65} (Tables 5, 6 and 7), which is consistent with previous isometric squat research (Bazyler *et al.* 2015; Palmer *et al.* 2017), with forces decreasing as the muscle length increased in the squat position (Beckham *et al.* 2018; Marcora and Miller 2000; Swinton *et al.* 2012). This stands to reason as ISq_{120} corresponds with the knee angle (~120°) that produces the greatest force during isolated knee extension (Thorstensson *et al.* 1976). Much like PIF, RFD does seem to increase with greater knee extension angle in some (Marcora and Miller 2000; Drake *et al*. 2019) but not all studies and appears to be more dependent on the time band used to quantify this variable rather than the knee angle at which the test is conducted (Brady *et al*. 2017; Palmer *et al*. 2017; Oranchuk *et al*. 2019). In the current study, differences in RFD (Table 8) between positions were not as pronounced compared to that of PIF variables (Tables 5, 6 and 7). No significant differences in RFD were observed between positions, with the exception of ISq_{120}, which was significantly greater than ISq_{65} on day 2 (Table 8).

MF displayed greater reliability compared to PIF, a finding that is consistent with previous literature (Brady *et al*. 2017; Drake *et al*. 2018). Presumably, this is because MF values are inclusive of subject body weight. Therefore, the same (or very similar) absolute differences in force between trials would lead to improved reliability for MF compared to PIF. However, for the purpose of monitoring force changes over time, PIF is likely the more important variable, capturing the true force production capacity of an individual.

In addition to producing the greatest force, based on ICC scores, the ISq_{120} position appeared to produce the most reliable data for MF, PIF and allometrically scaled PIF both within and between days (Tables 5, 6 and 7) (Atkinson and Nevill 1998; Bland and Altman 1990). Additionally, between-day PIF was greatest at ISq_{120} and whilst not significantly different from the other positions, the between-day CV for PIF was highest at ISq_{65}. However, this was not the case for RFD, with no clear differences in reliability between positions based on these data. Based on researcher observation and subjects' verbal feedback, it was reported that the ISq_{65} position was more difficult and unfamiliar for subjects to establish. Given the increased mobility demands of the ISq_{65}, some subjects had difficulty attaining the required positioning, which may have affected the quality of the data obtained. It is speculated that in contrast with the ISq_{65} position, the ISq_{120} and ISq_{90} positions requires minimal skill and mobility, allowing subjects to focus their efforts on exerting maximal force into the bar. However, it is plausible that a greater number of familiarization sessions may have improved the reliability in the ISq_{65} position (Drake *et al*. 2018). Although there were no observed learning or fatigue effects over time, either within- or between test days 1 and 2 (Tables 5, 6, 7 and 8, Figures 14 and 15), if the study was extended to more than three sessions (2 familiarisations + 1 test-session) the reliability for the ISq_{65} may have improved[1]. Drake *et al.* (2018) observed improvements in MF and PIF in the ISq at a 90° knee angle past three test days, indicating that more familiarisation sessions may be required in the 'deeper' and more unfamiliar isometric squat positions.

---

[1] Learning effects of the ISq and 1RM back squat are explored in Appendix 2.

To put the reliability data observed here in the context of the wider literature, in a group of resistance trained females Palmer *et al.* (2017) reported CV and ICC values of 12 % and 0.840 respectively for PIF at the ISq_{90} as well as CV and ICC values of 11.2 % and 0.839 respectively for PIF at the ISq_{120}, which closely approximates the results herein. The RFD data of Palmer *et al*. (2017) are also similar to that of the current investigation, with CV and ICC values of 19.4 % and 0.814 respectively reported for RFD during the 0-200ms time band at ISq_{90} as well as CV and ICC values of 15.9 % and 0.814 reported for RFD at ISq_{120}. It is worth noting that this was the most reliable RFD time band reported by Palmer *et al*. (2017), compared to 0-30, 0-50 and 0-100ms time bands.

Bazyler *et al.* (2015) report CV and ICC values for MF at ISq_{90} (CV = 2.9, ICC = 0.97) and ISq_{120} (CV = 3.0, ICC = 0.99) as well as an ICC of 0.90 for RFD (0-250ms time band) at ISq_{90} and ISq_{120} respectively in resistance trained males. Lum and Joseph (2019) reported ICC values of 0.99 and 0.98 for MF at ISq_{90} and ISq_{120} respectively, as well as ICC values of 0.87 and 0.84 for RFD (0-90ms time band) at ISq_{90} and ISq_{120} respectively. Blazevich *et al.* (2002) also reported an ICC of 0.97 for PIF in the ISq_{90} in resistance trained males. No RFD data were reported in their study. In contrast with these results, Drake *et al.* (2018) reported CV and ICC values of 6 % and 0.856 for MF as well as CV and ICC values of 4 % and 0.885 for PIF in the ISq_{90} (no RFD data reported). In a similar vein, Brady *et al.* (2017) reported CV and ICC values of 3.5 % and 0.98 for MF as well as CV and ICC values of 4.6 % and 0.97 for PIF at a 136° knee angle. In addition, CV and ICC values of 9.8 % and 0.86 were reported for RFD during the 0-250ms time band (Brady *et al*. 2017). Data from these two studies are more reliable than what is presented in the current study. However, it must be noted that these studies used highly trained individuals; indicating that training history or strength-level may have some effect on day-to-day ISq reliability. The greater knee extension angle utilised by Brady *et al*. (2017) may have also played a role in producing such high reliability, particularly for RFD. Additionally, differences in methodological approaches for obtaining force variables in the ISq may explain the disparity between the results presented here and that of other studies (Drake *et al.* 2018; Brady *et al*. 2017). Firstly, the subjects in Brady *et al*. (2018) and Drake *et al*. (2018) only performed two maximal effort ISq trials per test session, compared to three in the current study. Whilst the available evidence does not necessarily indicate that three trials is optimal, there is evidence to suggest that PIF in the ISq continues to increase beyond three test trials (Pekünlü and Özsu 2014), although crucially this was based on data from a single test session (i.e. no pre-familiarization). Nonetheless, it does suggest that performing only two ISq trials is a practice worth reconsideration. In addition, it is recommended to discard ISq or IMTP trials if there is a > 250 N difference between trials (Brady *et al*. 2019; Comfort *et al*. 2019). Discarding of such trials (despite no other obvious grounds for exclusion) would likely lead to more favourable reliability scores by virtue of removing outlier data. This was not done in the current study as the force variables were analysed after the testing session was completed. However, as outlined in Chapter 2, if an ineligible contraction was detected from the force read in real time (e.g. very obvious countermovement), then it was excluded and repeated. Given these differences in ISq test methodologies, coupled with the differences in subject strength training status; it seems apparent as to why the reliability data presented here differs to that of the aforementioned investigations (Drake *et al.* 2018; Brady *et al*. 2017).

Of the aforementioned ISq reliability studies, only three have reported TE values for the ISq. Brady *et al.* (2017) and Blazevich *et al.* (2002) reported TE values of 4.7 % and 3.0 % for PIF respectively, though both of these studies report much higher mean PIF values (2322 N and 2321 N respectively) compared to the values detailed here (see Table 6). This again suggests strength level and/or training-experience may affect the reliability of the measure. Brady *et al*. (2017) reported TE values of 9.6 % for RFD (0-250ms time band), which compares favourably with the results presented here (Table 8). Finally, Lum and Joseph (2019) report TE values of 4.0 % and 4.8 % for MF at ISq_{90} and ISq_{120} respectively as well as 8.6 % and 12.7 % for RFD at ISq_{90} and ISq_{120} respectively. The authors do not document the formula used to calculate TE, which could be viewed as a problem, as the ‘typical error’ can sometimes be conflated with estimates of TE (such as the CV).

3.6 Conclusions

Effective performance measurement is dependent upon the reliability of the measures used to monitor performance. This is the first study to examine the influence of ISq position on ISq measurement reliability in young, healthy men, as well as the first to investigate the ISq at a 65° knee angle. Moreover, this is also the first study that provides a direct comparison of the ISq_{65} with the more commonly utilized ISq_{120} and ISq_{90} positions. The novel finding of this study was that the observed reliability of the ISq_{65} was comparable with that of the more established ISq_{120} and ISq_{90} positions, indicating that it is appropriate to conduct the ISq in this position, if knowledge of force production capacity in this position is deemed to be of relevance to an investigator or practitioner. However, given the increased range of motion required to perform the ISq_{65} position (which may prove non-viable for some individuals), for general evaluation of lower body force production, those with the resources necessary to conduct ISq testing may consider using either the ISq_{120} or ISq_{90} position. Significantly greater force is produced in these positions compared to the ISq_{65}. By contrast, the data suggest that the reliability of PIF assessment in the ISq is likely not affected by the position at which the test is conducted. It is acknowledged that measures of explosive strength (i.e. RFD) are considerably less reliable and the majority of these data do not fall within the threshold CV of ≤ 10. Finally, the TE values reported here allow researchers and practitioners alike to determine what is the smallest change required over time to be considered real if they are working with subjects from the same population from which our sample was drawn. This is a valuable consideration for those using the ISq to monitor performance changes in response to training interventions.

As noted in the discussion, previous investigations with highly strength trained subjects have shown superior reliability (at least in terms of CV) in the ISq (Brady *et al*. 2017; Drake *et al*. 2018) suggesting that there may be an influence of strength level or training status on the reliability of ISq measurement, similar to what has been observed for 1RM back squat (Nuzzo *et al*. 2019). Previous ISq reliability studies have all been conducted on a relatively homogenous population of strength trained individuals (see Table 4), highlighting an area for future research investigating the role of strength training status as an independent variable on the reliability of ISq measurement. This supposition is explored in the next Chapter.

Chapter 4

4.0 Reliability of isometric squat force output in subjects of varying levels of strength and training experience

Preface

It is concluded from study 1 (Chapter 3) that the ISq_{65} demonstrates acceptable reliability for PIF assessment, and that the reliability of this position is comparable with the more well-established ISq_{120} and ISq_{90}. Knowledge of force production in the ISq_{65} may be of relevance for athletes in Powerlifting and Olympic Weightlifting who routinely perform the squat to this position as a requirement of their sport. However, during study 1, concerns were raised about the difficulty in establishing the ISq_{65} position among some subjects, which may be problematic for individuals who are taller and may not have the prerequisite mobility to perform this position. In such instances, an ISq_{120} or ISq_{90} may be more appropriate. Furthermore, in contrast with other measures of maximal strength such as the 1RM or the isometric mid-thigh pull, the currently available literature does not indicate to what degree the reliability of the ISq_{120} and ISq_{90} may be influenced by the maximal strength (as indicated by PIF in the ISq) and/or training status of an individual (as indicated by relative 1RM back squat strength and overall strength training experience). Therefore, the current investigation aimed to explore to what extent does maximal strength and training status influence the reliability of PIF in the ISq.

4.1 Abstract

The aim of this study was to investigate the relationship between maximal isometric squat (ISq) strength, as indicated by peak isometric force (PIF) and the between-day reliability of the measure as indicated by coefficient of variation (CV) and intraclass correlation coefficient (ICC). On two separate days, 59 healthy active men, aged 18 to 35 y with varying levels of maximal ISq strength, performed three maximal effort ISq trials at a 120° (ISq_{120}) and a 90° (ISq_{90}) knee angle. Acceptable reliability was observed for the entire group at both ISq_{120} (CV = 7.5 (6.7), ICC = 0.960 [0.933, 0.977]) and at ISq_{90} (CV = 9.2 (8.8), ICC = 0.920 [0.865, 0.953]). There was no relationship between maximal ISq force output and between-day reliability at either the ISq_{120} ($R^2 = 0.018$, $P = 0.327$) or ISq_{90} ($R^2 = 0.004$, $P = 0.613$). When subjects were divided into sub-groups based on training status, it was revealed that between-day reliability improved with increased training status (i.e. reliability of untrained < moderately trained < highly trained), however these differences in CV between sub-groups were not significant ($P \geq 0.146$). It is concluded that maximal strength does not appear to influence the reliability of PIF measurement in the ISq, a novel finding which supports the use of the measure across populations with varying levels of strength and training experience.

4.2 Introduction

Traditional measures of maximal strength of the lower body such as 1RM back squat testing may be unsuitable in certain circumstances due to both practical and methodological issues surrounding the conduct of 1RM back squat testing; in particular the control of the range of motion and the reliability of the test in certain populations (Bazyler *et al*. 2014; Nuzzo *et al*.

2019). The latter is highlighted by the susceptibility of 1RM to systematic bias (i.e. learning effects) (Nuzzo *et al*. 2019). Furthermore, reliability of 1RM testing tends to improve with increased subject training experience and strength level (Nuzzo *et al*. 2019). Conversely, the ISq presents a credible alternative to 1RM back squat testing for the assessment of maximal lower body strength, as it allows for the fixation of the ISq position and has demonstrated acceptable reliability (< 10 % CV, ≥ 0.8 ICC) previously within this thesis as well as elsewhere (Bazyler *et al*. 2015; Drake *et al*. 2018).

The nature of the test indicates a lower skill demand compared to the 1RM, which suggests the ISq would display good test-retest (or between-day) reliability, regardless of the maximal strength level and/or training status of an individual. However, to the best of current author’s knowledge, no previous study has investigated the relationship between the reliability of PIF measurement in the ISq and the maximal strength level (and more often than not by association training status) of an individual. A distinction is made between maximal strength and training status, as the expression of strength is highly task specific (Buckner *et al*. 2017). For example, differing results have been observed for increases in strength following a training intervention when comparing two different tests of the same agonist muscle group, often with marked differences between intervention groups based on one test and no differences between groups based on another test. Sale *et al*. (1992) observed a 29.1 % increase in 1RM leg press strength in a group of previously untrained individuals, compared to a non-training control group. However, no changes in isometric maximum voluntary contractile force of the knee extensors were observed in either group. Similar results were observed by Mitchell *et al*. (2012), who reported greater 1RM knee extension increases in subjects training at a higher intensity (80 % vs. 30 % of 1RM), with no between-group differences for increases in isometric maximum voluntary contractile force of the knee extensors. This bears relevance to the current investigation, as differences in strength between individuals based on 1RM strength (as a result of their habitual training practices) may not be as apparent in the ISq, due to unfamiliarity with the test.

In Chapter 3, acceptable reliability was observed in the ISq across different positions (CV ≤ 9 %, ICC ≥ 0.836, Table 5). In addition, available data for the ISq indicates acceptable reliability of the measure across different investigations (Tillin *et al*. 2013; Bazyler *et al*. 2015; Palmer *et al*. 2019; Drake *et al*. 2018). However, most of the available literature is heavily weighted towards moderately trained individuals, with little data available on the tail ends of the strength training experience spectrum (i.e. untrained and highly-strength trained individuals) (see Table 4 of Chapter 3). Therefore the current study aimed to investigate the relationship between maximal ISq strength, measured by peak isometric force (PIF) output and the reliability of ISq measurement. *A priori* it was hypothesised that ISq reliability would be influenced by maximal ISq strength. As an additional, secondary objective, the influence of training status (i.e. untrained vs. recreationally trained vs. highly trained) on ISq reliability was also analysed.

4.3 Methods

Subjects

The study design, documentation and procedures were all approved by the University of Limerick Education and Health Sciences Research Ethics Committee, in accordance with the declaration of Helsinki (ethical approval number EHS_2016_12_09). Prior to inclusion subjects were informed of the benefits and risks of participation before providing written informed consent. Eligibility criteria were: (i) men, (ii) 18 to 35 years of age, (iii) habitually active and in good general health with no current injuries, illness or history of disease. An open recruitment policy was adopted, meaning that no prerequisite strength training status or strength level was required to participate in the study.

Subjects were categorized based on strength training status post-recruitment. In total, a heterogeneous sample of 59 male subjects (mean (SD) age 23.0 (4.1) years, body mass 84.0 (15.2) kg, height 1.79 (0.7) m) were recruited from the local area and voluntarily took part in the study. Subjects had a mixed strength training age (range: 0-13 years of strength training experience) in order for the investigation to be valid. The sample was comprised of 8 untrained subjects (no prior strength training experience), 42 moderately strength trained subjects (≥ 6 months strength training experience, back squat 1RM < 1.5 × body mass), and 9 highly strength trained subjects (competitive Powerlifters, ≥ 3 years strength training experience, competition back squat 1RM ≥ 2.0 × body mass within the previous 3 months of participation in the current study, which was confirmed via online records [https://www.openpowerlifting.org]). Descriptive statistics for the sub-groups are displayed in Table 9.

Variable	**Mean (SD)**		
	Untrained	**Moderately Trained**	**Highly Trained**
Sample Size	8	42	9
Age (y)	22 (3.6)	23.1 (4.2)	23.4 (2.2)
Body Mass (kg)	75.6 (7.8)	85.1 (16.2)	87.4 (11.3)
Height (cm)	180.4 (7.8)	179.4 (7.7)	176.9 (6.6)
Strength Training Experience (y)	N/A	4.7 (3.8)	5.8 (2.9)
Baseline Absolute 1RM (kg)	N/A	107.1 ± 16.4	199.5 ± 21.7 *
Baseline Relative 1RM (kg · kg^{-1})	N/A	1.2 ± 0.2	2.3 ± 0.3

Table 9 – Descriptive statistics for the sub-groups. 1RM = one repetition maximum back squat. * based on online records of most recent Powerlifting competition.

Design

Using a single-group repeated measures design, the relationship between PIF in the ISq and the between-day reliability of ISq measurement was analysed. All subjects performed three maximal effort ISq contractions in two different ISq positions on two test days, separated by at least 72 h (range: 72-168 h).

Procedures

Subjects reported to the lab each test day at the same time (10:00 to 14:00) to minimize any confounding effects of time of day on strength (Grgic *et al*. 2019). Eligibility and familiarisation with the test procedures was undertaken 24 to 72 h prior to starting the study. Subjects were instructed to maintain their normal eating habits throughout the study. Dietary intake was recorded prior to the first test day and each subject was instructed to repeat this intake before the second test day. In addition, subjects were instructed to refrain from any formal lower body exercise 48 h prior to testing.

The specific procedures for the conduct of ISq testing are outlined in Chapter 2, section 2.2.

ISq testing was conducted in the ISq_{120} and ISq_{90} positions. The rationales for using these two positions have been outlined elsewhere (Bazyler *et al*. 2015). In short, ISq_{120} replicates the strongest position of the back squat (McLaughlin *et al*. 1977), whereas ISq_{90} correlates highly with 1RM back squat weight lifted (Bazyler *et al*. 2015; Blazevich *et al*. 2002). Both positions have received substantial attention within the literature and have demonstrated high reliability in certain populations (Bazyler *et al*. 2015; Drake *et al*. 2018; Palmer *et al*. 2017). Thus it was decided to use both positions for the purpose of this investigation.

Testing order for the two positions was randomized for each subject on the first test day and this same order was repeated on the second test day. Three maximal effort ISq contractions were performed in each position. Vertical ground reaction force data were sampled at 1 kHz and excluded if any countermovement was evident. Absolute PIF (N) was determined as the highest value attained out of the three attempts on each test day.

Statistical analyses

Between-day (day 1 *vs*. day 2) reliability scores were calculated for absolute PIF for all subjects, analysed as one group (n = 59). Normality and homogeneity of variance was assessed prior to analysis. A two-way random model with absolute agreement was used to calculate the intra-class correlation coefficient (ICC) (Koo and Li 2016). An ICC over 0.9 was defined as highly reliable, between 0.8 and 0.9 as moderately reliable, and below 0.8 as not reliable (Atkinson and Nevill 1998; Bland and Altman 1990). Between-day coefficient of variation (CV) was also calculated by dividing the standard deviation by the mean, expressed as a percentage. A CV of < 10 % is generally accepted as reliable (Nuzzo *et al*. 2019). Paired samples t-tests were used to compare PIF and CV between positions (ISq_{120} vs. ISq_{90}). To assess the relationship between maximal ISq strength and the reliability of PIF measurement, a correlation and regression analysis was conducted by plotting subjects' absolute PIF scores at ISq_{120} and ISq_{90} against their respective CV scores in each position. Finally, in order to examine any influence of training status on the reliability of PIF measurement, subjects were divided into distinct sub-groups based on their strength training status (i.e. untrained vs. moderately trained vs. highly trained), with reliability data (CV and ICC) calculated for each sub-group. Welch's t-tests were then used to compare differences in CV between sub-groups, with the alpha level set at $P < 0.05$.

4.4 Results

Reliability data for all subjects analysed as one group are presented in Table 10. Based on the < 10 % CV threshold, the data achieved acceptable reliability (Table 10). In addition, based on ICC data all variables achieved high reliability, with all variables reaching an ICC > 0.9 (Table 10).

Correlation and regression analyses of the between-day reliability revealed no relationship between maximal ISq strength and ISq reliability at either ISq_{120} ($R^2 = 0.018$, $P = 0.327$) or ISq_{90} ($R^2 = 0.004$, $P = 0.613$) as shown in Figure 16.

Tables 11 and 12 represent the reliability of absolute PIF in the ISq as a function of subject training status (i.e. untrained vs. moderately trained vs. highly trained) at ISq_{120} and ISq_{90} respectively. When presented in this manner, a trend was observed for greater reliability with increased training status (i.e. reliability of the untrained < moderately trained < highly trained), particularly at ISq_{120} (see Table 11). However, differences in CV between sub-groups were not significant, based on Welch's t-tests ($P \geq 0.146$).

Peak isometric force			
	Day 1 **(N)** **Mean (SD)**	**Day 2** **(N)** **Mean (SD)**	**Difference** **Day 2 – Day 1 (N)** **Mean [LLOA, ULOA]**
ISq_{120}	1579 (536)	1536 (567)	-11 [-724, 703]
ISq_{90}	1035 (298) ^{a}	958 (275) ^{a}	42 [-430, 514]
Between-Day Reliability			
	CV [mean (SD)]	**ICC [95 % CI]**	
ISq_{120}	7.5 (6.7)	0.960 [0.933, 0.977]	
ISq_{90}	9.2 (8.8)	0.920 [0.865, 0.953]	

Table 10 – Reliability of peak isometric force at ISq_{120} and ISq_{90} for all subjects (n = 59). LLOA = lower limits of agreement, ULOA = upper limits of agreement, CV = coefficent of variation, ICC = intraclass correlation coefficient, 95% CI = 95% confidence interval, ^{a} = significantly different peak isometric force from the ISq_{120} position ($P < 0.001$).

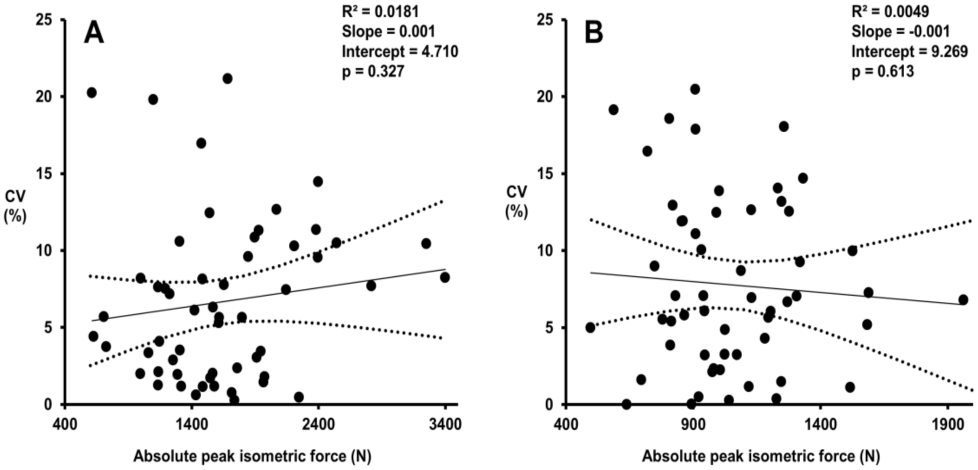

Figure 16 – Correlation and regression analyses of maximal ISq strength (PIF) and reliability via CV in the isometric squat. **A** represents the reliability of between-day PIF (highest values of day 1 and day 2) at ISq_{120}, plotted against the corresponding CV values. **B** represents the reliability of between-day PIF (highest values of day 1 and day 2) at ISq_{90}, plotted against the corresponding CV values. Dashed lines indicate the 95% confidence intervals.

Peak isometric force at ISq$_{120}$			
	Day 1 (N)	**Day 2 (N)**	**Difference Day 2 – Day 1 (N)**
	Mean (SD)	**Mean (SD)**	**Mean [LLOA, ULOA]**
Untrained	924 (335) $^{MT, HT}$	845 (287) $^{MT, HT}$	-25 [-102, 53]
Moderately trained	1716 (485) ^{UT}	1674 (549) ^{UT}	-36 [-109, 37]
Highly trained	1557 (492) ^{UT}	1510 (367) ^{UT}	-47 [-154, 59]
Between-day reliability			
	CV [Mean (SD)]	**ICC [95% CI]**	
Untrained	10.3 (9.9)	0.907 [0.537, 0.981]	
Moderately trained	7.7 (6.3)	0.946 [0.899, 0.972]	
Highly trained	4.2 (3.8)	0.963 [0.837, 0.992]	

Table 11 – Reliability of peak isometric force across differing training statuses at ISq$_{120}$. ^{UT} = significantly different peak isometric force from untrained sub-group ($P < 0.05$), ^{MT} = significantly different peak isometric force from moderately trained sub-group ($P < 0.05$), ^{HT} = significantly different peak isometric force from highly trained sub-group ($P < 0.05$).

Peak isometric force at ISq$_{90}$

	Day 1 (N) Mean (SD)	**Day 2 (N) Mean (SD)**	**Difference Day 2 – Day 1 (N) Mean [LLOA, ULOA]**
Untrained	666 (124) $^{MT, HT}$	650 (213) $^{MT, HT}$	-19 [-146, 108]
Moderately trained	1095 (289) ^{UT}	1002 (261) $^{UT, 1}$	-90 [-141, -38]
Highly trained	1096 (207) ^{UT}	1026 (226) ^{UT}	-68 [-136, -1]
	Between-Day Reliability		
	CV[Mean (SD)]	**ICC [95% CI]**	
Untrained	9.1 (6.0)	0.917 [0.519, 0.986]	
Moderately trained	8.6 (7.5)	0.901 [0.813, 0.948]	
Highly trained	7.4 (3.9)	0.941 [0.736, 0.987]	

Table 12 - Reliability of peak isometric force across differing training statuses at ISq$_{90}$. ^{UT} = significantly different peak isometric force from untrained sub-group ($P < 0.05$), ^{MT} = significantly different peak isometric force from moderately trained sub-group ($P < 0.05$), ^{HT} = significantly different peak isometric force from highly trained sub-group ($P < 0.05$). ^{1} = significantly different PIF from day 1 ($P < 0.05$).

4.5 Discussion

Training status and by association maximal strength has previously been shown to influence the reliability of strength measures such as the 1RM squat and leg press (Nuzzo *et al*. 2019; Benton *et al*. 2013; Ritti-Dias *et al*. 2011). Though previous literature has documented the reliability of a variety of ISq tests across different populations with varying levels of maximal strength, no previous study has investigated the relationship between maximal ISq strength and the reliability of the measure (Bazyler *et al*. 2015; Blazevich *et al*. 2002; Brady *et al*. 2018; Drake *et al*. 2018; Hart *et al*. 2012;

Palmer *et al*. 2017; Pekünlü *et al*. 2014; Tillin *et al*. 2013). Therefore, the aim of this study was to test the hypothesis that maximal strength influences the reliability of PIF measurement in the ISq. Acceptable levels of reliability for PIF for the entire sample of 59 subjects are reported here (CV ≤ 9 %, ICC ≥ 0.920, Table 10) based on previously established reliability cut-offs of > 0.8 ICC and < 10 % CV (Atkinson and Nevill 1998; Beckham *et al*. 2018; Nuzzo *et al*. 2019). Regression analyses for between-day CV at ISq_{120} and ISq_{90} revealed no relationship between maximal ISq strength (as indicated by PIF) and ISq reliability (Figure 16). Therefore, the *a priori* hypothesis is rejected and it is inferred that maximal strength does not affect the reliability of PIF measurement in the ISq.

When subjects were divided into sub-groups based on their training classification at the time of enrolment in the study, reliability appeared to improve with increased training status, although these differences were not statistically significant (Tables 11 and 12). When subjects were divided in this manner, some variables fell outside the reliability threshold of < 10 % CV observed in the initial analysis of the entire group. Interestingly, PIF did not scale with training status in a manner that would have been expected prior to commencing the investigation (Tables 11 and 12). Mean PIF values for the moderately trained sub-group did not differ from that of the highly trained sub-group at either ISq_{120} (Day 1 $P = 0.526$; Day 2 $P = 0.347$, Table 11) or ISq_{90} (Day 1 $P = 0.845$; Day 2 $P = 0.195$, Table 12). This finding is somewhat at odds with previous literature, where ISq and 1RM have both been reported amongst relatively stronger and weaker sub-groups based on 1RM squat strength (Bazyler *et al*. 2014; Drake *et al*. 2018). However, this finding may also point to the specific nature of the ISq compared to the 1RM back squat, whereby an individual is skilled in the performance of the back squat, but unfamiliar with the ISq. Due to this unfamiliarity with the ISq it is likely that any differences in strength based on 1RM are somewhat reduced by the specific demands of the ISq. This narrative is supported by Buckner *et al*. (2017), who note that when strength is measured in a test that both subject groups are naïve to, differences in strength are not as apparent. For the purpose of classifying subjects in the current study, 1RM squat strength was used as an independent variable, whereas ISq PIF was the dependent variable. When classified in this manner, PIF in the ISq did not differ between the moderately trained and highly trained individuals. In addition, the observed correlation between ISq and 1RM (r = 0.63-0.86; Table 2 of Chapter 1) further suggests that whilst similar, there two tests are distinct. Conversely, the observed lower PIF values of the untrained sub-group compared to the other sub-groups suggests that there is at least some degree of generality in strength adaptation (Buckner *et al*. 2019).

Though no previous studies have directly investigated the relationship between maximal ISq strength and the reliability of ISq measurement, ISq reliability studies across different populations with distinct levels of strength are available to place the findings of this study in context. Tillin *et al*. (2013) is the only available study that measured ISq force variables in two distinct subject sub-groups of differing strength levels (18 elite male athletes and 8 untrained male subjects, with the ISq conducted at a mean knee angle of 118°), however between-day reliability data were only obtained from the untrained subjects (4 % CV and 0.960 ICC). These reliability data in untrained subjects fall within the acceptable range as reported here. In a group of recreationally trained male subjects (≥ 1 year training experience), Bazyler *et al*. (2015) observed similar between-day reliability scores at ISq_{120} (2.9 % CV and 0.970 ICC) and ISq_{90} (3.0 % CV and 0.990 ICC) respectively (although these were for MF and not PIF). Though not directly comparable, this suggests that recreational training experience does not influence ISq reliability. Similarly, Drake *et al*. (2018) reported comparable between-day CV and ICC values of 6.1 % and 0.856 for PIF at ISq_{90} in a group of strength trained males (mean (SD) training experience 4.1 (1.8) years), suggesting training status, and by association maximal strength, may not influence ISq reliability. Similarly, Blazevich *et al*. (2002) reported a between-day ICC of 0.97 in the ISq_{90} in a group of athletic men. Finally, Palmer *et al*. (2017) reported CV and ICC values of 11.2 % and 0.839 respectively for PIF at ISq_{120} as well as 12 % and 0.885 for PIF at ISq_{90} respectively in a group of resistance trained females. The between-day reliability data from Palmer *et al*. (2017) differs quite considerably from the rest of the available literature, though the differences may be explained by the use of female subjects as opposed to any influence of strength on the reliability of the measure. The data reported here display similar levels of reliability as measured by CV and ICC, and support the observation that maximal ISq strength does not appear to influence reliability of the ISq. This appears to be consistent across positions (ISq_{120} and ISq_{90}) as reported here and elsewhere (Bazyler *et al*. 2015; Blazevich *et al*. 2002; Drake *et al*. 2018).

According to Hopkins (2000) for many measurements used in sports science and sports medicine, as the value for a measure increases, so does its error value (typically expressed as a CV). This suggests that stronger individuals may produce less reliable data. However, evidence indicates that the reliability of 1RM tests of maximal lower body strength (i.e. squat, leg press etc.) improves with increased training status (and consequently increased weight lifted) (Nuzzo *et al*. 2019; Benton *et al*. 2013; Ritti-Dias *et al*. 2011).

Conversely, the isometric mid-thigh pull (IMTP), a test that is very similar to the ISq does not appear to be influenced by maximal strength (based on PIF). Beckham *et al*. (2018) found stronger, experienced (mean (SD) MF 4587.1 (981.8) N) and weaker, inexperienced (3493.9 (568.2) N) subjects produced equivalent between-day reliability data (experienced subjects 1.9 % CV, 0.996-0.997 ICC; inexperienced subjects 2.8 % CV, 0.984-0.985 ICC). These data support the observation of the current study that maximal strength does not affect the reliability of an IMJT (see Figure 16). The observed disparity between the influence of maximal strength on the reliability of isometric multi-joint tests (i.e. ISq and IMTP) versus that of 1RM may be better explained by the training history of an individual rather than their maximal strength per se. This is also supported by the data presented here, whereby maximal strength did not influence the reliability of PIF measurement in the ISq, but the reliability of PIF measurement increased with increased strength training status (Tables 11 and 12). Buckner *et al*. (2017) classify 1RM as a specific skill, whilst also making the argument that a true measure of strength remains elusive. However, given the likely lower skill demand of the ISq in addition to the unfamiliarity with the ISq across all subjects (i.e. a 'trained' individual may be familiar with a dynamic squat but have no prior exposure to the ISq), this may help explain why reliability is consistent in the current investigation despite considerable variation in PIF across the entire sample.

4.6 Conclusion

In this study, acceptable levels of reliability were reported in an ISq test conducted at knee angles of 120° and 90°; providing additional evidence that the measure is a reliable test of maximal strength. Regression analyses demonstrate that the reliability of PIF measurement in the ISq is not influenced by the maximal strength level of an individual. This is an important finding for sport science researchers and practitioners as it adds merit to the applicability of ISq measurement across differing strength levels. Where an assessment of lower body maximal strength is desired, but conventional 1RM back squat assessment is deemed to be inappropriate (e.g. in untrained subjects), the ISq offers a reliable alternative. For practitioners the ISq offers a potential alternative to typical 1RM testing, which can be difficult to standardise and carries an inherent level of risk in an untrained population that may not be deemed acceptable.

Chapter 5

5.0 The sensitivity of the isometric squat test to detect training induced changes in maximal strength

Preface

Studies 1 and 2 have established the reliability of the ISq_{120} and ISq_{90}. Both assessments demonstrate acceptable reliability for PIF and are in-line with the reliability assessments of other ISq tests. What is currently less well-established in the literature is the sensitivity of the ISq to training induced changes in maximal strength. As outlined in Chapter 1, reliability and sensitivity are related but distinct, in that a measure can be reliable and not sensitive. For the purpose of monitoring performance over time, measurement sensitivity is a characteristic that is of great importance. Therefore, the current study aimed to build on the previous experimental studies by establishing the sensitivity of the ISq_{120} and ISq_{90} to training induced changes in maximal strength following a short term strength training intervention.

5.1 Abstract

The objective of this study was to assess the sensitivity of an ISq to strength training induced changes in maximal strength, as indicated by changes in PIF. Moderately strength trained men (n = 18, 1RM back squat = 107.2 (15.9) kg, strength training experience = 5.0 (4.6) y) underwent 6 weeks of progressive strength training. PIF in the ISq_{120} and ISq_{90} as well as 1RM back squat weight lifted were assessed pre and post-training. Changes were compared to pre-determined TE values for each outcome measure (ISq_{120} = 10.9 %, ISq_{90} = 13.9 %, 1RM = 4.4 %) to see if observed changes were outside the measurement error associated with each test. Increases in strength were significant as well as being greater than the TE for each outcome measure following training (ISq_{120} = 17.4 (20.5) %, $P = 0.002$; ISq_{90} = 13.4 (17.0) %, $P = 0.003$; 1RM = 13.6 (6.8) %, $P < 0.0001$). In conclusion, the ISq appears to be sensitive to strength training induced changes in lower body maximal strength, following a 6 week training intervention.

5.2 Introduction

The aim of any exercise training intervention is to improve one or more desired fitness components. The adaptation to the intervention is specific to the nature of the training program that is implemented as well as the measurement test used to assess changes in the fitness component(s) of interest (Campos *et al*. 2002; Sale 1988; Hawley 2008). Measurement tests ought to be valid (i.e. measure what they intend to measure) as well as reliable (able to reproduce the same results in the same subjects under the same conditions) (Currell and Jeukendrup 2008). Additionally, for the purpose of monitoring changes in fitness over time, researchers and/or practitioners would benefit from knowing the sensitivity of a test prior to implementation. The sensitivity of a test (also termed "responsiveness") relates to its ability to detect practically relevant changes over time (Impellizzeri and Marcora 2009; Currell and Jeukendrup 2008). This may be viewed as the smallest change over time that could be considered real (i.e. outside the range of measurement error typically associated with a test) and is of great importance in outcome based research (Gonzalo-Skok *et al*. 2015).

In order to determine what this smallest change in performance over time that can be considered real, the variation in performance needs to be determined; specifically the within-subject variation. The lower the within-subject variation, the smaller the change required to be considered real (Hopkins 2000). As such, reliability and sensitivity are distinct but related constructs, as the sensitivity of a test is dependent on its reliability. Conversely, a test can be deemed reliable but if it is unable to detect small, meaningful changes over time, its use is questionable (Gonzalo-Skok *et al*. 2015). As an example, Maffiuletti et al. (2007) document the apparently high test-retest reliability of isometric and isokinetic knee extension dynamometry (CV $\leq$ 5.5 %, ICC $\geq$ 0.972). However, these same strength measures have also shown poor sensitivity to detect strength changes following a training intervention (Sale *et al*. 1992; Murphy and Wilson 1997). Sale (1992) observed increases of 29.1 % for the 1RM leg press, with no change in peak isometric knee extension torque. Murphy and Wilson (1997) measured changes in 1RM back squat weight lifted and isokinetic knee extension torque following an 8 week training intervention in a group of recreational athletes (mean baseline 1RM back squat 1.4 × body mass). Markedly differing strength responses were observed following training (4 % reduction vs. 21 % increase for peak torque and 1RM squat respectively).

Maximal lower body strength can be assessed using a number of different isometric and/or dynamic measures. In recent years, IMJT measures that replicate important positions of corresponding dynamic free-weight based strength exercises have received increased attention in outcome based studies assessing changes in maximal strength in response to a training intervention. This includes exercises such as the ISq (Drake *et al*. 2017). These tests are appealing for outcome based studies due to their safety, and the degree of measurement control that they offer. The observed correlations between ISq peak force and 1RM back squat weight lifted (r = 0.63-0.86, see Table 2 of Chapter 1), coupled with the biomechanical similarity between the two tests suggests the ISq is a valid assessment of maximal lower body strength (Bazyler *et al*. 2015). In addition, the ISq test has repeatedly demonstrated acceptable test-retest (or between-day) reliability (CV < 10 %, ICC > 0.8) (Bazyler *et al*. 2015; Blazevich *et al*. 2002; Brady *et al*. 2017; Drake *et al*. 2018). In Chapters 3 and 4, high test-retest reliability in the ISq was also observed (CV ≤ 10 %, ICC ≥ 0.892).

Reliability statistics can be used to indicate the change scores required to be considered “real” over time (Hopkins *et al*. 2000; Weir *et al*. 2005). This could then be viewed as an index of the sensitivity of the ISq. Furthermore, the typical response of ISq measured maximal strength following a training intervention has been previously investigated (Wilson *et al*. 1993; Alegre *et al*. 2006; Bazyler *et al*. 2014; Lum and Joseph 2019). However, with the exception of Lum and Joseph (2019), to the author’s knowledge, no other studies have provided the necessary between-day reliability statistics to be able to place their results within the context of the typical error of the measurement. Therefore, whilst a change may be significant (i.e. $P < 0.05$), it may not be greater than the error that is typically associated with the test. The current study aimed to determine the sensitivity of an ISq test to detect changes in maximal strength in response to an ecologically valid strength training intervention, as indicated by statistically significant changes in PIF, beyond the TE of the measurement. In addition, to provide context for the sensitivity of the ISq, a comparison of the response of the ISq to 1RM back squat weight lifted was included, as this is a commonly used measure in this application.

5.3 Methods

Design

Using a single-group repeated measures design the effects of an ecologically valid, whole body free-weight based strength training program on PIF in the ISq and 1RM back squat weight lifted were assessed. Prior to commencing training, subjects conducted a familiarisation protocol with all strength measures, which was then used to determine the change scores required to be considered “real” (i.e. outside the typical error range of the measurement) following the training intervention.

Subjects

The study design, documentation and procedures were all approved by the University of Limerick Education and Health Sciences Research Ethics Committee, in accordance with the declaration of Helsinki (ethical approval number 2019_01_05_EHS). Inclusion criteria were as follows: (i) male, (ii) 18 to 35 y, (iii) in good general health with no current injuries, illness or history of disease, (iv) recreationally strength-trained; operationally defined as $\geq$ 6 months free-weight based strength training experience and a 1RM back squat $<$ 1.5 × body mass. In total, 19 male subjects volunteered to participate in the study. One of the volunteers exceeded the 1RM squat strength inclusion criterion and therefore did not proceed to the training intervention, leaving a total of 18 subjects. Subject characteristics are displayed in Table 13.

Variable	Mean (SD)
Sample size	18
Age (y)	23.3 (3.2)
Body mass (kg)	88.3 (15.0)
Height (cm)	180.3 (7.8)
Baseline absolute 1RM (kg)	107.2 (15.9)
Baseline relative 1RM (kg • kg^{-1})	1.2 (0.1)
Baseline absolute ISq$_{120}$ PIF (N)	1708.1 (553.2)
Baseline relative ISq$_{120}$ PIF (N • kg^{-1})	19.8 (6.3)
Baseline absolute ISq$_{90}$ PIF (N)	932.5 (195.5)
Baseline relative ISq$_{90}$ PIF (N • kg^{-1})	12.6 (3.3)

Table 13 – Subject characteristics and baseline maximal strength levels. 1RM = one repetition maximum back squat, PIF = peak isometric force.

5.3.1 Procedures

Eligibility, familiarisation and baseline testing days

Following written informed consent as well as a full explanation of the benefits and risks of participating in the study, subjects were invited to the lab to conduct the familiarisation test session with the outcome measures (ISq and 1RM). ISq testing was performed first, followed by the 1RM squat. Subjects were instructed to refrain from any formal lower body exercise for 48 h prior to testing. In addition, subjects were instructed to maintain their normal eating habits throughout the study. Dietary intake was recorded prior to the familiarisation test day and each subject was instructed to repeat this intake for each subsequent test day. Following the familiarisation test day, subjects returned to the lab a minimum of 72 hours later and repeated the ISq and 1RM testing protocol (baseline test day). The between-day differences in PIF (i.e. highest value from the familiarisation test day and the baseline test day) and 1RM scores were used to calculate TE (outlined below in section 5.3.2).

Isometric squat testing

The procedures for the conduct of the ISq testing are outlined in depth in Chapter 2, section 2.2.

ISq testing was conducted at the ISq_{120} and ISq_{90} positions. Both of these positions have been used in previous ISq investigations (Bazyler *et al*. 2014; Bazyler *et al*. 2015; Drake *et al.* 2018; Lum and Joseph 2019) and the reliability of these positions across various investigations has previously been outlined within this thesis (Table 4 and Figure 13 of Chapter 3). In addition, the between-day reliability of these positions was reported in Chapter 3 (CV ≤ 9 %, ICC ≥ 0.892) and Chapter 4 (CV ≤ 9 %, ICC ≥ 0.920). Once the two ISq positions were established, each subject was randomly assigned to perform 3 maximal effort isometric contractions at either ISq_{120} or ISq_{90} first before performing a further 3 maximal effort contractions in the other ISq position. This order was then repeated on each subsequent test day to ensure within-subject consistency. Subjects completed three sub-maximal warm up ISq contractions in the first position (either ISq_{120} or ISq_{90}) prior to measurement (50 %, 70 % and 90 % of perceived maximal effort) which were maintained for at least 3 s with a 1 min rest between each ISq (Beckham *et al*. 2018). For each maximal effort ISq, subjects were given standard verbal encouragement from the investigators, who instructed subjects to "push as hard and fast as possible into the bar" and to maintain peak force output for the duration of the contraction. At the onset of the audible cue the contraction started and subjects were encouraged by the experimenters to maintain a 3 s contraction. 3 min of rest was given between each ISq attempt to minimize fatigue accumulation (Willardson 2006).

1 repetition maximum back squat testing

The procedures for the 1RM test are outlined in depth in Chapter 2, section 2.3.

Training and re-testing

Subjects performed bilateral whole body, free-weight based strength training twice per week for 6 weeks, as outlined in Table 14. This intervention length has previously been shown to be effective for increasing 1RM back squat weight lifted (Lamont *et al*. 2011; Styles *et al*. 2016) as well as PIF in the ISq_{120} and ISq_{90} (Lum and Joseph 2019). Sets and reps were progressed in a similar fashion to that of Bazyler *et al*. (2014). Back squat training load was set at 70 % of 1RM in the first training session and the load was progressively increased between sessions as appropriate, with subjects' RPE maintained between 8 and 9 (i.e. 1 to 2 repetitions in reserve) between weeks 1-5, with RPE's of 9.5 achieved in week 6. The lack of significant increase in ISq measured PIF from Alegre *et al*. (2006) may have been related to the low intensity of their training protocol, which did not exceed 60 % of 1RM. Therefore in the current study, a distinctly higher intensity approach was adopted. Following completion of the training phase and a minimum of 72 h of recovery, subjects returned to the lab to re-test ISq_{120}, ISq_{90} and 1RM.

5.3.2 Statistical analyses

Normality and homogeneity of variance was assessed prior to data analysis. Reliability was determined from the CV and ICC. The CV was calculated by dividing the standard deviation by the mean, multiplied by 100, with a CV < 10 % generally considered to be reliable (Nuzzo *et al*. 2019). A two-way random model with absolute agreement was used to calculate ICC, with an ICC > 0.9 considered to be highly reliable, between 0.8 and 0.9 as moderately reliable, and < 0.8 as not reliable. Change scores required to be considered "real" (i.e. outside the normal error range of the measurement) were derived from the TE for ISq_{120}, ISq_{90} and 1RM respectively. TE was calculated by dividing the standard deviation of the between-day difference scores by √2 (Hopkins 2000). Paired samples t-tests were conducted to determine statistically significant changes ($P < 0.05$) in ISq_{120}, ISq_{90} and 1RM from baseline to post-training. Effect size (d) was calculated for changes in PIF at ISq_{120} and ISq_{90} as well as changes in 1RM weight lifted following training by dividing the mean of the change scores by the standard deviation of the change scores (Dankel and Loenneke 2018). The magnitudes of these were classified as small (0.2), medium (0.5) or large (0.8) (Cohen 1988).

Training day	Exercise	Week 1 & 2		Week 3 & 4		Week 5 & 6	
		Sets	**Reps**	**Sets**	**Reps**	**Sets**	**Reps**
1	Barbell back squat	3	6	3	4	4	2
	Barbell bench press	3	8	3	6	3	4
	Barbell deadlift	3	6	3	5	3	4
	Barbell row	3	10	3	8	3	6
2	Barbell back squat	3	6	3	4	4	2
	Barbell bench press	3	8	3	6	3	4
	Barbell semi-straight leg deadlift ("RDL")	3	8	3	6	3	4
	Barbell row	3	10	3	8	3	6

Table 14 – Outline of the 6 week strength training program.

5.4 Results

Between-day reliability and typical error

The reliability analysis yielded acceptable between-day reliability data for ISq_{120} (CV = 8.1, ICC = 0.938), ISq_{90} (CV = 8.1, ICC = 0.857) and 1RM (CV = 4.1, ICC = 0.974) respectively (see Table 15). TE values indicated that change scores of 10.9 %, 13.9 % and 4.4 % for ISq_{120}, ISq_{90} and 1RM respectively would be required following training. As previously discussed, reliability and sensitivity are related but distinct constructs. This is highlighted in Table 15, whereby similar reliability (% CV) and sensitivity (% TE) scores are reported for each outcome measure. However, the CV and TE values differ to a greater degree in the ISq (particularly at ISq_{90}), reiterating the point that despite the obvious numerical similarity, CV and TE are distinct metrics, which provides justification for the use of the latter in this paradigm.

	CV (SD)	ICC [95% CI]	TE (absolute value)	TE (% change)
ISq_{120}	8.1 (6.5)	0.938 [0.868, 0.971]	186.6 N	10.9 %
ISq_{90}	8.1 (8.1)	0.857 [0.696, 0.933]	143.0 N	13.9 %
1RM	4.1 (3.9)	0.974 [0.947, 0.988]	4.5 kg	4.4 %

Table 15 – Between-day reliability and typical error of all outcome measures. CV = coefficient of variation, ICC = intraclass correlation coefficient, TE = typical error.

Changes in maximal strength measures following training

Significant increases in ISq measured PIF were observed at ISq_{120} (mean (SD); 17.4 (20.5) %, $P = 0.002$, $d = 0.8$) and ISq_{90} (mean (SD); 13.4 (17.0) %, $P = 0.003$, $d = 0.8$) and these are shown in Table 16. Increases in 1RM were also significant (mean (SD); 13.6 (6.8) %, $P < 0.001$, $d = 2.1$). The increases in ISq_{120}, ISq_{90} and 1RM, relative to the TE determined at baseline are displayed in Figure 17 (mean response) and Figure 18 (individual response). The correlation between the percent changes in each outcome measure is displayed in Figure 19. The correlation between percentage changes at ISq_{120} and 1RM as well as the correlation between percentage changes in ISq_{90} and 1RM were both negligible ($r \leq 0.09$), whereas a strong correlation was observed for changes at ISq_{120} and ISq_{90} ($r = 0.80$). Finally, Figure 20 displays the correlations between initial strength levels and changes in strength for each outcome measure. Weak to moderate inverse correlations ($r \leq -0.45$) were observed between initial strength levels and changes in strength (Figure 20).

	ISq_{120}	**ISq_{90}**	**1RM**
Baseline [**Mean (SD**)]	1708.1 (553.2) N	932.5 (195.5) N	107.2 (15.9) kg
Post-training [**Mean (SD**)]	1951.2 (516.4) N	1044.9 (215.9) N	121.9 (19.5) kg
Change [**Mean (SD**)] %	17.4 (20.5) %	13.4 (17.0) %	13.6 (6.8) %
[95 % CI] Δ	[100.3, 385.8] N	[42.5, 182.3] N	[11.0, 18.2] kg
[95 % CI] %	[5.9, 22.6] %	[4.6, 19.5] %	[10.3, 17.0] %
P	0.002	0.003	<0.0001
d	0.8	0.8	2.1

Table 16 – Maximal strength changes following training. 95 % CI = 95 % confidence interval, Δ = change (absolute value).

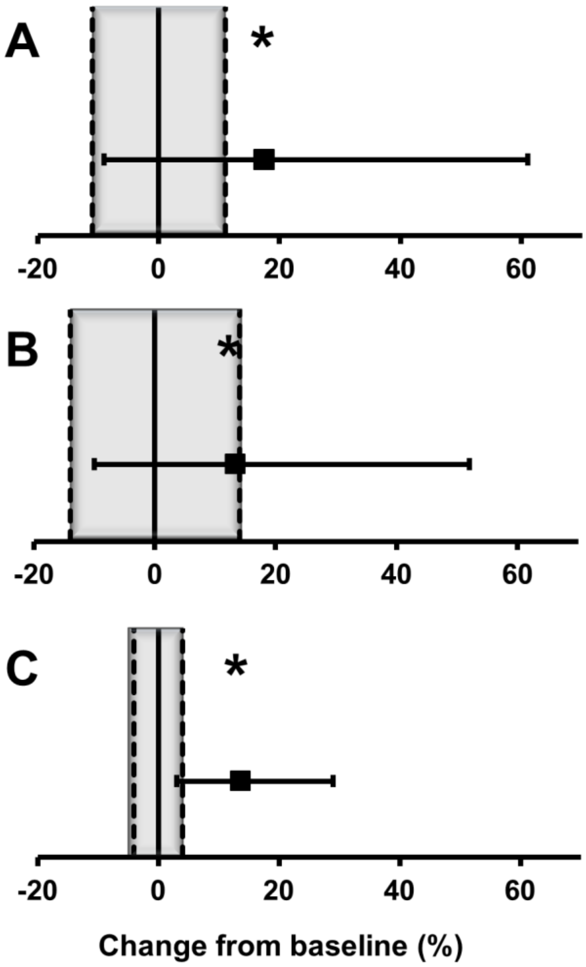

Figure 17 – Changes in maximal strength following training, expressed as mean [95 % confidence interval]. **A** represents changes in PIF at ISq_{120}, **B** represents changes in PIF at ISq_{90}, **C** represents changes in 1RM weight lifted. Grey area represents the range of typical error for each outcome variable (i.e. scores outside this range can be considered “real”). * indicates significant change from baseline ($P < 0.05$).

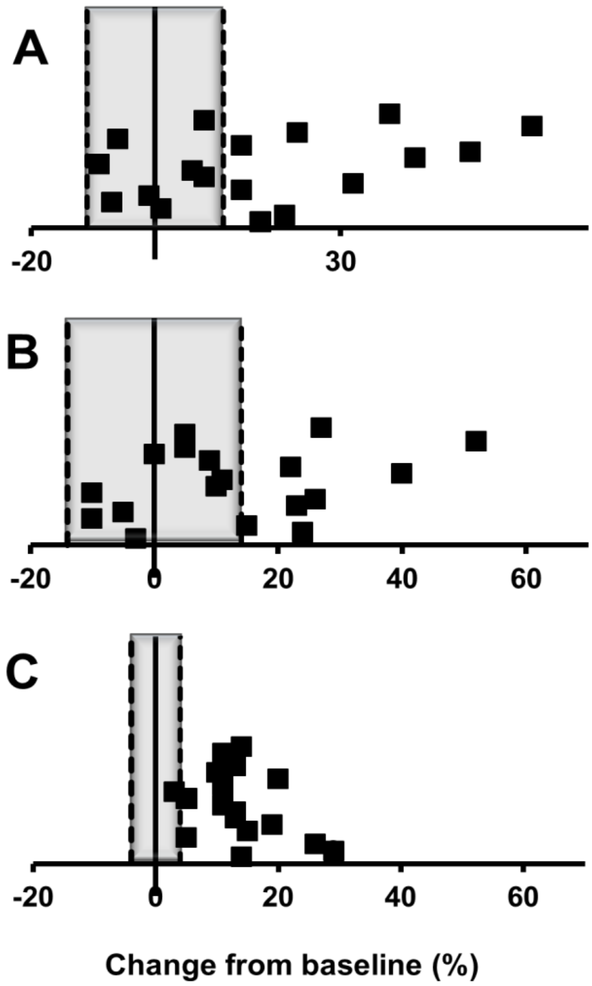

Figure 18 – Individual maximal strength responses following training. **A** represents change in PIF at ISq_{120}, **B** represents change in PIF at ISq_{90}, **C** represents change in 1RM weight lifted. Black boxes indicate individual percentage changes relative to baseline. Grey area represents the range of typical error for each outcome variable (i.e. scores outside this range can be considered "real").

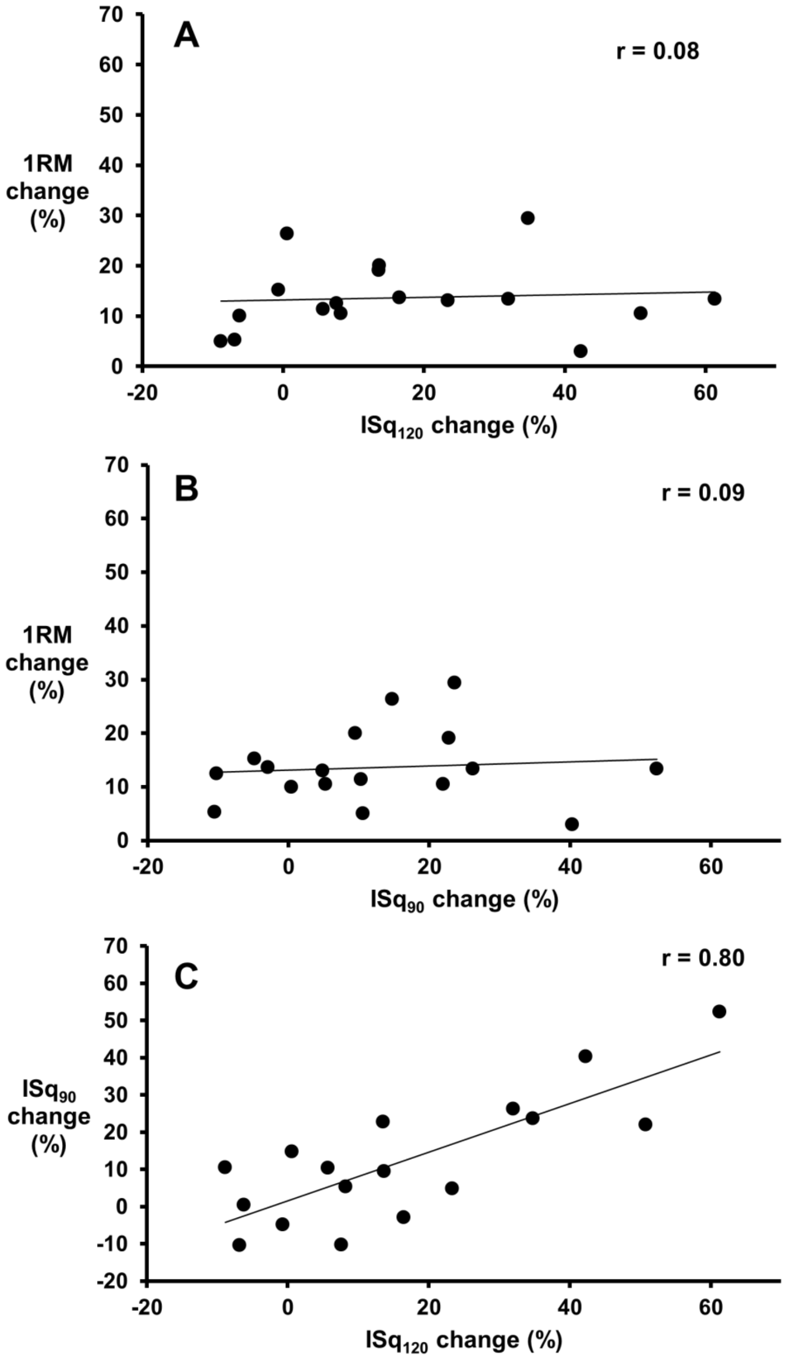

Figure 19 – Correlations between the percentage changes in each outcome measure**. A** represents the change at ISq$_{120}$ and 1RM, **B** represents the change at ISq$_{90}$ and 1RM, **C** represents the change at ISq$_{120}$ and ISq$_{90}$.

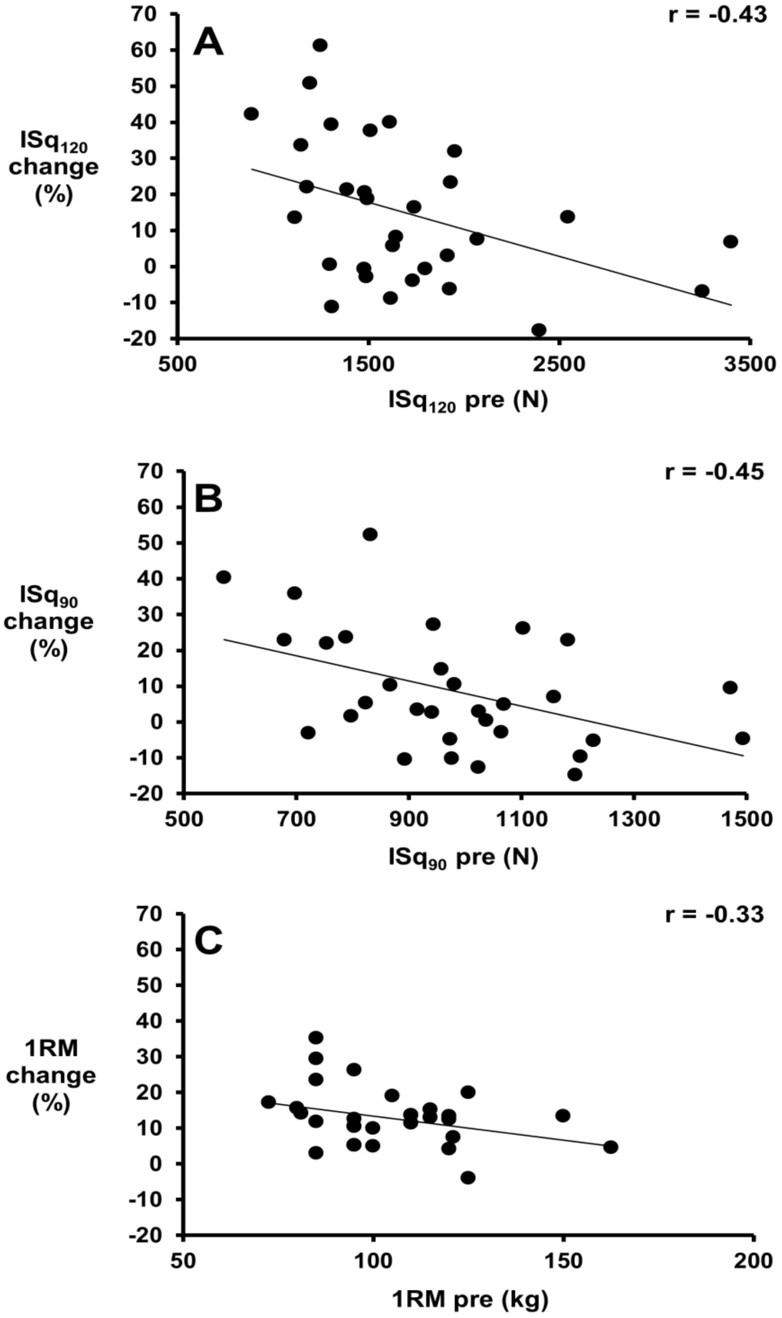

Figure 20 – Correlations between initial strength levels (x-axes) and changes in strength (y-axes) for each outcome measure**. A** represents the initial strength and change in strength at ISq_{120} respectively, **B** represents the initial strength and change in strength at ISq_{90} respectively, **C** represents the initial strength and change in strength in the 1RM respectively.

5.5 Discussion

The aim of this study was to determine the sensitivity of an ISq test to training induced changes in maximal strength, as indicated by changes in PIF. Results for the ISq were compared to 1RM, as the latter is a measure of maximal strength that is commonly used in this application. Based on the data collected at baseline (see Table 13), pre-training PIF values were comparable with that of other studies at ISq_{120} (Tillin *et al.* 2013) as well as ISq_{90} (Newton *et al*. 2002). Based on the results of the paired samples t-tests, significant ($P < 0.05$) increases in maximal strength were observed in the ISq_{120}, ISq_{90} and 1RM (Table 16). In addition, the mean changes for each outcome measure were all greater than the TE values that were determined prior to the training intervention, indicating that the mean changes in maximal strength were real (i.e. greater than the error associated with the respective measures, see Figure 17). Conversely, when the individual responses were assessed, changes in ISq_{120} and ISq_{90} displayed greater variability compared to that of 1RM (Figure 18). Following training, all 18 subjects increased 1RM weight lifted above the 4.4 % TE value (Figure 18 C), whereas 10 of the 18 subjects achieved an increase in PIF at ISq_{120} that was greater than the 10.9 % TE (Figure 18 A) and only eight subjects had an increase in PIF at ISq_{90} that was greater than the 13.9 % TE (Figure 18 B).

To put these results in the context of the wider literature, Lum and Joseph (2019) observed increases of 15.9 % and 9.5 % for ISq_{120} and ISq_{90} respectively following a training program performed twice per week for 6 weeks in a group of trained floorball athletes. Pre-determined TE values at baseline were 4.8 % and 4.0 % for ISq_{120} and ISq_{90} respectively. The lower

TE values observed by Lum and Jospeh (2019) may be attributable to using within-day reliability data as opposed to between-day reliability data (i.e. two trials within the same day vs. two trials performed on separate testing days). Nonetheless the magnitude of increase in ISq measured PIF is similar to that observed in the current study. Cormie *et al.* (2007) observed increases of 14.2 (3.4) % and 11.8 (7.2) % for 1RM and ISq measured PIF at a 100° knee angle following 8 weeks of training in a group of eight recreationally trained male subjects. Both of these increases were statistically significant, though no reliability data were provided to infer whether or not these changes were outside the measurement error associated with these tests. Markovic *et al.* (2007) reported a significant increase of 10 % at ISq_{120} following 10 weeks of training in a group of 30 physical education students. Wilson *et al*. (1993) saw a significant increase in ISq measured PIF (conducted at a 135° knee angle) of 14.4 % following 10 weeks of training in a group of trained male subjects. In both of these studies, no TE values were reported, meaning the results cannot be viewed within the context of the inter-day biological variation in test performance. However the magnitudes of the increases are comparable with that of the current study. By contrast, Alegre *et al*. (2006) observed an increase of 4.8 % for ISq measured PIF at a 90° knee angle ($P > 0.05$) and an increase of 8.2 % in 1RM back squat ($P < 0.05$) following 13 weeks of training twice per week in a group of previously untrained males. The Alegre *et al*. (2006) study stands out somewhat as the increases in PIF were considerably lower than what has typically been observed elsewhere (Bazyler *et al*. 2014; Cormie *et al*. 2007; Lum and Joseph 2019; Markovic *et al*. 2007; Wilson *et al*. 1993). Interestingly, despite being 13 weeks long, the intensity of the training intervention did not exceed 60 %, which may help explain their results as intensities of > 60 % of 1RM are required to increase strength in trained individuals (Rhea *et al.* 2003; Schoenfeld *et al*. 2017).

Perhaps the most similar study design to the current investigation is that of Bazyler *et al.* (2014). Subjects were divided into two groups, one group trained with full range of motion squats whereas the other group trained with full + partial range of motion squats (from a 100° knee angle to full extension). Training was performed twice per week for 7 weeks. Both groups significantly increased full range of motion 1RM (5.1-8.2 %) and partial range of motion 1RM (10.2-14.9 %) squat following training, with no differences between groups. However, changes in ISq measured PIF were training dependent. The group training with full + partial range of motion squats increased ISq_{120} by 8.9 (8.6) % and the group training with full range of motion squats increased ISq_{90} by 5.3 (4.5) %. Changes in PIF at ISq_{120} as a result of full range of motion squat training and changes in PIF at ISq_{90} as a result of full + partial range of motion squat training did not reach significance. Reasons for why the increases in PIF at ISq_{120} were only seen in the full + partial range of motion squat training group are unclear but may be somewhat related to the increased loading afforded by the partial range of motion squat training. The increased loading would require greater forces to be produced through the partial squat range of motion, which in turn may have resulted in an augmented adaptive response, as evidenced by the increases in PIF in this group, compared to those who only performed full range of motion squat training. Despite only incorporating full range of motion squats into the training, increases in PIF observed in the current investigation are similar to that of Bazyler *et al*. (2014). In their study, the magnitude of increase was smallest at ISq_{90} (5.3 (4.5) %) and although the mean increases for ISq_{120} and 1RM squat were similar (8.9 (8.6) vs. (8.2

(2.1) % respectively), there was less variation around the mean for increases in 1RM. Reasons for this are not entirely clear but may be at least partly explained by the greater specificity of back squat training to the 1RM back squat, compared to the ISq.

Overall, the data reported here suggest that of the three performance measures of interest, 1RM may be the most sensitive to detect training induced maximal strength adaptations, as the greatest increases were observed in the 1RM, with less variability compared to ISq_{120} and ISq_{90}. However, the ISq is still capable of detecting changes in maximal strength, following a 6 week training intervention that is non-specific to the ISq. A strong correlation was observed for the changes in PIF at ISq_{120} and ISq_{90} (r = 0.8, Figure 19). By contrast, correlations between changes in PIF at both ISq_{120} and 1RM as well as changes in PIF at ISq_{90} and 1RM were both negligible (Figure 19). This provides some additional support for the specific nature of the ISq and 1RM, a finding that was also observed and is discussed in Chapter 4. As outlined in the introduction, adaptations to training interventions are stimulus specific (Hawley 2008). Interestingly, the findings of Lum and Joseph (2019) resulted from a training protocol that included the use of the ISq as part of the training program (i.e. use of the ISq as a training exercise in conjunction with traditional dynamic strength exercises). In addition, no traditional back squat (or equivalent exercise) was performed as part of the training intervention (Lum and Joseph 2019). This would be an example of a training intervention that is very specific to the ISq and much less specific to the 1RM back squat (though this was not assessed as part of their investigation). It is plausible that if the current study had incorporated ISq training, either in place of or in conjunction with dynamic strength exercises then increases in ISq measured PIF may have been greater and more homogenous. However, this was not the objective of the current study as ISq training is not commonly performed in typical strength training practices. Nonetheless, future investigations may wish to explore the overall influence of training specificity on ISq measured PIF adaptations, as this is currently not well established.

5.6 Conclusions and practical applications

The results of the current study demonstrate the sensitivity of an ISq test to training induced changes in maximal strength, in the context of recreationally trained male subjects following a 6 week training intervention. It is concluded that the ISq is sensitive to detect training induced changes in PIF following a 6 week intervention. In addition, the magnitude of increase in ISq measured PIF was comparable with that of 1RM weight lifted, though the results for the latter displayed less variability around the mean. For practitioners, this study provides some insight into the increases in PIF in the ISq_{120}, ISq_{90} and/or 1RM required following training to be considered genuine and outside the range of error that is typically associated with these tests. In addition, the data indicate the responses of these tests to 6 weeks of ecologically valid strength training.

Chapter 6

6.0 The ability of the ISq to detect and monitor change in inter-limb asymmetry

Preface

During the conduct of study 1 (Chapter 3), the use of a dual force plate system facilitated the observation of inter-limb asymmetry in ISq measured PIF in this sample (n = 17). This was also observed in the subsequent investigation (Chapter 4, n = 59). Previous literature has identified marked inter-limb asymmetries as a potential risk factor for injury, though this link is somewhat tenuous. Conversely, it is plausible that a marked asymmetry in ISq measured PIF could be detrimental to performance. Previous literature indicates that strength training can be used to attenuate such asymmetries. Therefore, as a secondary objective of study 3 (Chapter 5), the inter-limb asymmetry response to the bilateral strength training intervention was explored, the results of which are detailed in this Chapter. This sparked further exploration into the use of strength training interventions for the purpose of attenuating inter-limb asymmetries in ISq measured PIF. The current study aimed to assess the effects of a unilateral strength training intervention on inter-limb asymmetries in PIF as well as measures of maximal strength. Therefore, the intervention was designed in an identical fashion to the bilateral strength training intervention, differing only in the exercises performed by the subjects.

6.1 Abstract

The purpose of this study was to evaluate the ability of the ISq to detect and monitor inter-limb asymmetries in PIF, following initial observation of the phenomenon (based on data from Chapter 3, n = 17). Firstly, the presence of inter-limb asymmetry was observed in 18 out 59 subjects in a group of male volunteers (based on data from Chapter 4). Following this observation, the effects of 6 weeks of bilateral strength training on inter-limb asymmetry were reported (based on data from Chapter 5, n =18). This was followed up by an investigation of the effects of 6 weeks of unilateral strength training on inter-limb asymmetry in moderately strength trained males (n = 13). The results of bilateral vs. unilateral strength training on inter-limb asymmetries in PIF were then compared. Inter-limb asymmetries were measured using the ISq_{120} and ISq_{90}, with symmetry index (SI) scores assessed pre and post training. When all subjects were analysed as part of their respective groups, no change in SI scores were observed following bilateral (mean (SD) change in SI score: ISq_{120} = -1 (6), P = 0.526, d = 0.15; ISq_{90} = -1 (6), P = 0.702, d = 0.09) or unilateral training (ISq_{120} = 3 (6), P = 0.093, d = 0.51; ISq_{90} = 1 (8), P = 0.798, d = 0.07). However, when a sub-analysis was performed on subjects who presented with ≥ 10 % SI scores at baseline, statistically significant effects were observed in subjects who performed bilateral training (ISq_{120} = -6 (4), P = 0.001, d = 1.35; ISq_{90} = -5 (5), P = 0.039, d = 0.99). Results for subjects who performed unilateral training were position specific (ISq_{120} = 2 (5), P = 0.379, d = 0.44; ISq_{90} = -8 (4), P = 0.026, d = 2.03). Overall, the ISq appears to be an appropriate test to use to both detect and monitor change in inter-limb asymmetries in PIF as a result of training. In addition, results demonstrate that strength training can

attenuate inter-limb asymmetries in a population with ≥ 10% asymmetry in PIF.

6.2 Introduction

Inter-limb asymmetries in sport science and performance

Bilateral (or inter-limb) strength asymmetry refers to the relative difference in maximal strength between an individual’s limbs (Impellizzeri *et al*. 2007). These asymmetries may be the result of a combination of neurobiological and developmental causes as well as adaptations resulting from training (Owens 2011). Inter-limb asymmetry is a phenomenon that has received increased attention within the literature in recent years (Bishop *et al*. 2017; Bishop *et al*. 2018a; Maloney *et al*. 2019). Whilst their overall relevance within sport science is currently not well-understood, inter-limb asymmetries in force production have been observed in a variety of performance tests; namely strength, jumping and change of direction based tasks (Owens 2011; Bailey *et al*. 2013; Bazyler *et al*. 2014; Impellizzeri *et al*. 2007; Bell *et al*. 2014; Loturco *et al*. 2019; Bishop *et al*. 2020). As outlined in Chapter 1, marked asymmetries may heighten injury risk and/or potentially be of detriment to performance, although neither of these links are consistent (Bishop et al. 2018a). Furthermore, any associations between asymmetries and potential injury risk or reduced performance are both test and variable specific (Bishop *et al*. 2018b). For athletes who need to produce force bilaterally and symmetrically (e.g. powerlifters, weightlifters, strongmen etc.); any marked asymmetries in force production could conceivably be of detriment to performance as, in this context, performance is equal to the sum of the force produced by the two limbs simultaneously.

Therefore, any deficits between limbs would be reflected in the total force produced (Maloney 2019).

Early observations of inter-limb asymmetry in force production during the isometric squat

The presence of inter-limb asymmetry in ISq measured PIF was initially observed amongst subjects who volunteered to participate for study 1 (see Chapter 3). Not only was inter-limb asymmetry prevalent amongst these subjects, but depending on the position, up to 12 % of subjects presented with an asymmetry that was ≥ 10 % (Table 17), which may be considered meaningful in the context of overall performance (Hewitt *et al*. 2012; Bell *et al*. 2014). A summary of the inter-limb asymmetry data for PIF in the ISq in these subjects is provided in Table 17 below.

Inter-limb asymmetry for all subjects		
Position	**n**	**SI score [mean (SD)]**
ISq_{120}	17	5.9 (3.9)
ISq_{90}	17	5.7 (3.7)
ISq_{65}	17	4.8 (4.2)
Subjects with ≥ 10 % inter-limb asymmetry		
Position	**N**	**SI score [mean (SD)]**
ISq_{120}	1	14
ISq_{90}	2	12 (1.4)
ISq_{65}	2	13.5 (0.7)

Table 17 –Inter-limb asymmetry of peak isometric force in the isometric squat. Based on data from study 1 (Chapter 3). SI score = symmetry index score.

The potential application of the ISq to detect changes in inter-limb asymmetries in response to strength training

Given the observation of inter-limb asymmetry in ISq measured PIF, coupled with the available literature suggesting a possible deleterious effect of marked asymmetry on performance (Maloney 2019), this sparked further inquiry into the potential for strength training to attenuate such asymmetries, which could be measured using the ISq. Previous research using the ISq has not only shown the presence of inter-limb asymmetries in force production using the ISq, but has also reported changes in inter-limb asymmetries following a training intervention (Bazyler *et al*. 2014). In their study, bilateral squat training was employed over the course of a 7 week training intervention (performed twice per week), with the effects on overall ISq and 1RM performance as well as inter-limb asymmetry assessed post-training. Whilst this study shows promise for the use of the ISq in this application, no subsequent investigation into this topic has followed on from the work of Bazyler *et al*. (2014). Little is known about the potential effects of other strength training routines (e.g. unilateral strengthening exercises) on inter-limb asymmetries and subsequent performance.

Notwithstanding the lack of available evidence, other recent literature suggests that the unilateral equivalent of typically performed bilateral strength training exercises have the potential to reduce inter-limb asymmetries. In a case study by Brown *et al*. (2017), unilateral strengthening exercises were prescribed for the weaker limb for 6 weeks, with the effects on inter-limb asymmetries assessed post-training. These exercises included the single leg Romanian deadlift, single leg hip thrust and a single leg squat. The intervention reduced horizontal force asymmetry from 16 to 13 %, with a concomitant increase in horizontal force production and maximal running velocity. However, it is worth reiterating that this was a case study of an individual athlete, limiting the overall generalisability of the findings.

In a comparison of bilateral and unilateral training interventions, unilateral squat and jump exercises were more effective at reducing bilateral limb deficits (based on inter-limb differences in maximum power and change of direction ability) in male basketball players (Gonzalo-Skok *et al.* 2017). However, none of the tests used to assess asymmetry (which included a change of direction ability tests and a maximum back squat power test) were tests of maximal strength, an important consideration in the discussion of asymmetry given its highly task-specific nature. An observed asymmetry in a power or change of direction ability test is not necessarily equivalent with a test of maximum strength (Bishop *et al*. 2020). In addition, back squat and rear foot elevated split squat training produced equivalent performance increases in a group of academy rugby players (Speirs *et al*. 2016). Remarkably, this included increases in 1RM back squat. This provides some support for the exploration of unilateral strength training in the current paradigm.

Overall the available literature suggests there is potential merit for the use of unilateral exercises such as the rear foot elevated split squat in place of the back squat for reducing asymmetry as well as increasing strength performance. Additionally, evidence shows potential merit to the addition of balance and stability training on inter-limb asymmetries in hopping tests (Sannicandro *et al*. 2014) as well as isokinetic knee extension and flexion strength (Iacono *et al*. 2016). Unilateral free-weight based strength exercises such as the rear foot elevated split squat and the single leg Romanian deadlift pose much greater balance and stability demands compared to their bilateral counterparts, which may also strengthen the case for their inclusion in a strength training intervention aimed at reducing inter-limb asymmetries in strength.

Aims of the current investigation

The aim of this investigation was fourfold:

1. To examine the presence and magnitude of inter-limb asymmetries in a group of young men of varying levels of strength and training experience.
2. To investigate the effects of bilateral strength training on inter-limb asymmetries in PIF.
3. To investigate the effects of unilateral strength training on inter-limb asymmetries in PIF.
4. To compare the effects of bilateral and unilateral strength training on inter-limb asymmetries in PIF.

6.3 Methods

6.3.1 Measurement of inter-limb asymmetry using the ISq

As outlined in Chapter 2, section 2.2, use of a dual force plate system allows for the measurement of PIF in both limbs, such that any deficits between limbs can be detected. Figure 21 shows an example force time curve for an individual subject with a marked inter-limb asymmetry in PIF during a maximal effort ISq contraction. The deficit between the force-time curves for the individual limbs is analogous to the aforementioned adaptation window of opportunity (Maloney 2019, see section 1.5 of Chapter 1).

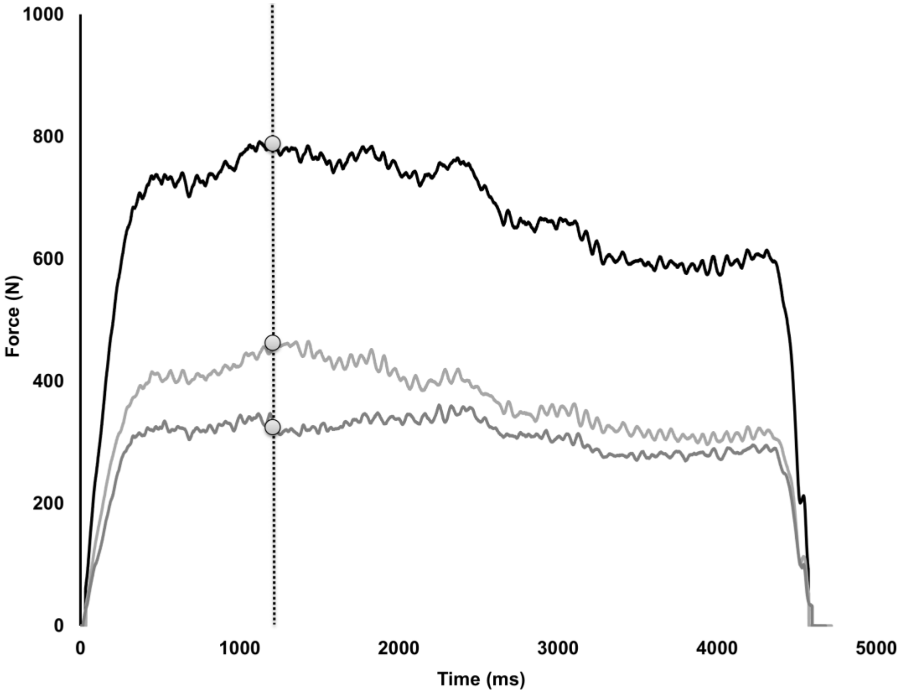

Figure 21 – Example force-time curve displaying the presence of inter-limb asymmetry in peak isometric force during a maximal effort isometric squat test. Black curve represents the force trace of both limbs combined, whereas the two grey curves display the force trace for the individual limbs. Dashed line and grey circles represent the instant at which the peak isometric force is obtained, with the corresponding value at each limb. The deficit between limbs could be considered the adaptation window of opportunity (Maloney 2019).

Inter-limb asymmetry in the ISq was determined using the symmetry index (SI), as described by Sato and Heise (2012) and Bishop *et al*. (2016). This is a commonly used formula for calculating inter-limb asymmetries (Sato and

Heise 2012; Bazyler *et al*. 2014) and is recommended for bilateral performance tests (Bishop *et al*. 2018c). The SI is calculated as follows:

$$SI = \frac{\text{Larger value} - \text{smaller value}}{\text{Total}} \times 100$$

6.3.2 Subjects

1. Asymmetry in PIF in subjects of varying levels of strength and training experience

As outlined in Chapter 4.

2. Detection and monitoring of inter-limb asymmetry using the ISq in response to bilateral strength training

As outlined in Chapter 5.

3. *Detection and monitoring of inter-limb asymmetry using the ISq in response to bilateral strength training*

Inclusion criteria were as follows: (i) male, (ii) 18 to 35 years of age, (iii) in good general health with no current injuries, illness or history of disease, (iv) recreationally strength-trained; operationally defined as ≥ 6 months free-weight based strength training experience and a 1RM back squat < 1.5 × body mass. It was chosen not to exclusively recruit asymmetrical subjects for the purpose of the investigation, but rather to randomly recruit a similar number of subjects from the same, moderately strength trained population as that of the bilateral strength training group, given that 7 out of the 18 subjects in that group presented with a baseline SI score of ≥ 10 in ISq measured PIF in this cohort (38.9 %, see Table 21). In total, 22 male subjects volunteered to participate and met the inclusion criteria for the study. Two subjects were lost during the training phase due to injury (one related to the training, the other unrelated to the training). Finally, due to restrictions enforced during the Covid 19 pandemic, a further 7 subjects were lost during the training phase. This left a total of 13 remaining subjects who completed the unilateral training intervention. Subject characteristics are displayed in Table 18.

Variable	Mean (SD)
Sample size	13
Age (y)	22.2 (3.9)
Body mass (kg)	80.7 (16.1)
Height (cm)	179.8 (6.7)
Baseline absolute 1RM (kg)	100.2 (25.2)
Baseline relative 1RM (kg • kg^{-1})	1.2 (0.1)
Baseline absolute PIF at ISq_{120} (N)	1651.8 (568)
Baseline relative PIF at ISq_{120} (N • kg^{-1})	20.2 (6.3)
Baseline absolute PIF at ISq_{90} (N)	1054.3 (300.8)
Baseline relative PIF at ISq_{90} (N • kg^{-1})	12.9 (3.6)

Table 18 – Characteristics of subjects who completed the unilateral strength training program.

6.3.3 Procedures for the subjects performing the strength training interventions

Baseline performance and asymmetry data

Following written informed consent as well as a full explanation of the benefits and risks of participating in the study, both bilateral and unilateral training groups performed a familiarisation and baseline test session, during which PIF in the ISq_{120}, and ISq_{90} as well as 1RM back squat weight lifted were obtained, as outlined in Chapter 2, sections 2.2 and 2.3 respectively. Inter-limb asymmetry was determined from the individual force-time curves (i.e. corresponding with the left and right limbs, as shown in Figure 21) from the contraction that the PIF value was derived from during the baseline test session (i.e. the strongest of the 3 ISq contractions). Inter-limb asymmetry was determined using the symmetry index (SI), as described by Sato and Heise (2012) and Bishop *et al*. (2016). SI scores were determined after the testing session, with the results blinded from the subjects to control for any bias that this may have caused.

Given how the direction of asymmetry has been shown to fluctuate (Bishop *et al*. 2020), it is important to denote the left or right side as being the stronger or weaker side. For the purpose of this investigation, SI scores that were ≥ 10 % at baseline were considered to be 'meaningful'. This was chosen for a number of reasons. Firstly, some evidence has shown this cut-off to be of relevance to injury risk (Orchard *et al*. 1997; Bell *et al*. 2014) though it is acknowledged that this is not always the case (Hewitt *et al*. 2012). Secondly, a ≥ 10 % cut-off may be linked to lowered performance levels (Bell *et al*. 2014). Additionally, concerns have been raised around the overall relevance of inter-limb asymmetries, in particular with respect to whether or not they can be considered genuine. With this in mind, Bishop *et al*. (2020) recommend reporting asymmetry values in conjunction with the overall variability (i.e. % CV values) of the test used. The ISq_{120} and ISq_{90} tests used to calculate asymmetry have both demonstrated CV reliability of < 10 %, meaning that a 10 % cut-off is outside the error range that is typically observed in these tests.

6.3.4 Training interventions and re-testing

Bilateral training group (N = 18)

Subjects performed bilateral, free-weight based strength training twice per week for 6 weeks. The training program is outlined is outlined in Chapter 5, Table 14. Following completion of the training phase and a minimum of 72 hours of recovery, subjects returned to the lab to re-test ISq_{120}, ISq_{90} and 1RM, with post-training SI scores obtained for ISq_{120} and ISq_{90}.

Unilateral training group (N = 13)

Subjects performed unilateral, free-weight based strength training twice per week for 6 weeks. The training program is outlined in Table 19. The unilateral strength exercises were performed on both limbs, with the load and range of motion matched between limbs. Additionally, the lower body exercises within the training program were volume and effort matched with the bilateral training program used in Chapter 5. Effort was manipulated by matching the RPE of the unilateral exercises with that of the bilateral exercises (i.e. RPE 8-9 in weeks 1-5, RPE 9.5 in week 6). Following completion of the training phase and a minimum of 72 hours of recovery, subjects returned to the lab to re-test ISq_{120}, ISq_{90} and 1RM, with post-training SI scores obtained for ISq_{120} and ISq_{90}.

		Week 1 & 2		Week 3 & 4		Week 5 & 6	
Session Number	**Exercise**	**Sets**	**Reps**	**Sets**	**Reps**	**Sets**	**Reps**
1	Barbell rear foot elevated split squat	3	6	3	4	4	2
	Dumbbell bench press	3	9-10	3	8-9	3	5-7
	Barbell single leg Romanian deadlift	3	8	3	6	3	4
	Dumbbell row	3	9-10	3	8-9	3	5-7
2	Barbell rear foot elevated split squat	3	6	3	4	4	2
	Dumbbell bench press	3	9-10	3	8-9	3	5-7
	Barbell single leg Romanian deadlift	3	8	3	6	3	4
	Dumbbell row	3	9-10	3	8-9	3	5-7

Table 19 – Outline of the 6 week unilateral strength training program. Note that the barbell rear foot elevated split squat and single leg deadlift were performed on both legs, using the same absolute load.

6.3.5 Statistical analyses

Normality and homogeneity of variance were assessed prior to analysis. Paired samples t-tests were conducted to determine statistically significant changes ($P < 0.05$) in asymmetry at ISq_{120} and ISq_{90} in both training groups from baseline to post-training. In addition, separate paired samples t-tests were conducted to determine statistically significant changes in asymmetry at ISq_{120} and ISq_{90} in the sub-groups of subjects who presented with ≥ 10 % SI scores at baseline. Effect size (d) was calculated for changes in asymmetry at ISq_{120} and ISq_{90} following training by dividing the mean of the change scores by the standard deviation of the change scores (Dankel and Loenneke 2018). Paired samples t-tests were conducted to determine any significant changes in performance outcomes (i.e. PIF at ISq_{120} and ISq_{90} as well as 1RM weight lifted) following both training interventions. Independent samples t-tests were conducted to compare any between-group differences (i.e. bilateral vs. unilateral training) for changes in SI score in subjects who presented with ≥ 10 % asymmetry at baseline at ISq_{120} and ISq_{90} respectively. Finally, regression analyses were performed in order to determine any relationships between changes in asymmetry and changes in performance in the sub-groups of subjects who presented with baseline SI scores of ≥ 10 %.

6.4 Results

1. Presence of inter-limb asymmetries in subjects of varying levels of strength and training experience

Inter-limb asymmetries in PIF were observed among this cohort (n = 59). In addition, depending on the position, up to 18 of the 59 subjects presented with an asymmetry that was ≥ 10 %, which may be considered meaningful in the context of overall performance (Hewitt *et al*. 2012; Bell *et al*. 2014). The asymmetry scores for this cohort are summarised in Table 20 below.

Position	**n**	**SI score [mean (SD)]**
ISq_{120}	59	9.5 (6.4)
ISq_{90}	59	7.2 (6.3)
	Subjects with ≥ 10 % inter-limb asymmetry	
	n	**SI score [mean (SD)]**
ISq_{120}	18	15.2 (5.7)
ISq_{90}	14	14.6 (4.6)

Table 20 –Inter-limb asymmetry of peak isometric force in the isometric squat in subjects of varying levels of strength and training experience. SI score = symmetry index score.

2. Application of the ISq in detecting changes in inter-limb asymmetries in response to bilateral strength training

Baseline asymmetry scores for this group as well as the asymmetry response to training at ISq_{120} and ISq_{90} are displayed in Table 21. Whilst no change in asymmetry was observed among the whole group ($P \geq 0.526$, $d \leq 0.15$), a significant reduction in SI scores was observed amongst the sub-group who presented with an SI score of ≥ 10 % at baseline at both ISq_{120} ($P = 0.001$, $d = 1.35$) and ISq_{90} ($P = 0.039$, $d = 0.99$). Individual changes in inter-limb asymmetry in PIF for the bilateral training group are displayed in Figure 22.

Position	**n**	**SI score Pre-training**	**SI score Post-training**	**Δ**	***P***	***d***
ISq_{120}	18	8 (8)	8 (7)	-1 (6)	0.526	0.15
ISq_{90}	18	8 (6)	7 (5)	-1 (6)	0.702	0.09
Inter-limb asymmetry response for subjects with ≥ 10 % asymmetry at baseline						
Position	**n**	**SI score Pre-training**	**SI score Post-training**	**Δ**	***P***	***d***
ISq_{120}	7	15 (8)	10 (9)	-6 (4)	0.001	1.35
ISq_{90}	7	14 (4)	9 (6)	-5 (5)	0.039	0.99

Table 21 – Inter-limb asymmetry scores in the bilateral strength training group. SI score = symmetry index score, Δ = change in SI score. Note that positive Δ values indicate that asymmetry increased, negative Δ values indicate that asymmetry decreased.

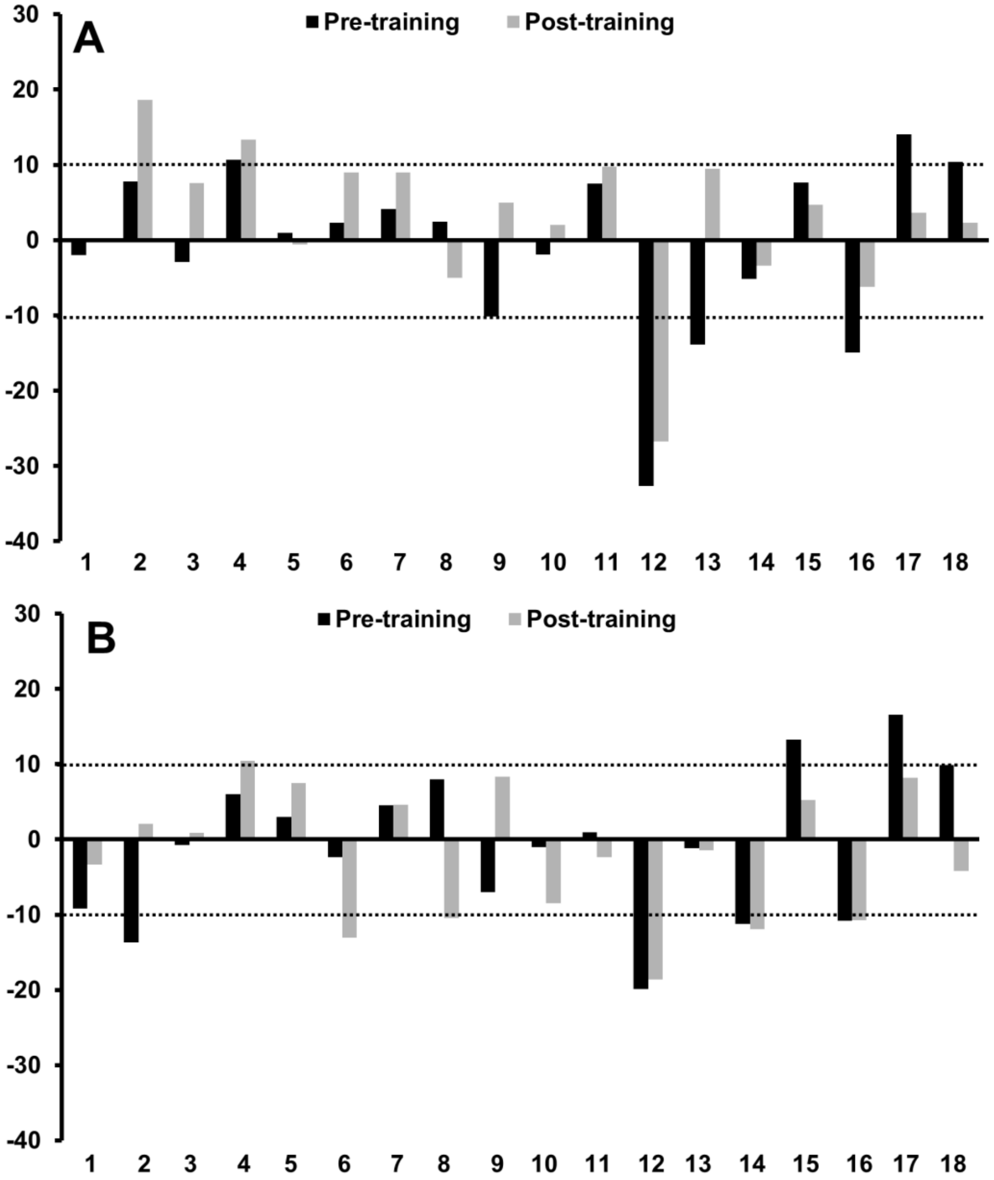

Figure 22 - Individual asymmetry data for isometric squat peak force in subjects who performed bilateral strength training (n = 18). **A** represents data from the ISq_{120}, **B** represents data from ISq_{90}. Black bars represent values pre-training, grey bars represent values post-training. Positive values indicate stronger right side, negative values indicate a stronger left side. Dashed line indicates the ≥ 10 % SI score cut-off.

3. Application of the ISq in detecting changes in inter-limb asymmetries in response to unilateral strength training induced and the effects of unilateral strength training on maximal strength performance

Baseline SI scores as well as changes in SI scores following the unilateral strength training program at ISq_{120} and ISq_{90} are displayed in Table 22. When the entire group was analysed, no significant changes in SI scores were detected following the training intervention ($P \geq 0.093$). Analysis of the sub-group with baseline SI scores of ≥ 10 % yielded position specific results for changes in inter-limb asymmetries (Table 22). Significant reductions in SI scores were observed at ISq_{90} ($P = 0.026$, $d = 2.03$, n = 4), although no significant changes were observed at ISq_{120} following training ($P = 0.379$, $d = 0.44$, n = 5). Individual changes in inter-limb asymmetry in PIF for the unilateral training group are displayed in Figure 23.

Increases in PIF and did not reach significance at ISq_{120} ($P = 0.08$, $d = 0.5$) or ISq_{90} ($P = 0.8$, $d = 0.1$) whereas increases in 1RM back squat weight lifted were significant ($P = 0.001$, $d = 1.3$) and comparable with that of the bilateral straining group presented in Chapter 5. The results for changes in ISq_{120}, ISq_{90} and 1RM in response to unilateral strength training are presented in Table 23.

Position	**n**	**SI score Pre-training**	**SI score Post-training**	Δ	***P***	***d***
ISq_{120}	13	10 (6)	13 (9)	3 (6)	0.093	0.51
ISq_{90}	13	8 (8)	8 (6)	1 (8)	0.798	0.07
Inter-limb asymmetry response for subjects with ≥ 10 % asymmetry at baseline						
Position	**n**	**SI score Pre-training**	**SI score Post-training**	Δ	***P***	***d***
ISq_{120}	5	16 (5)	18 (8)	2 (5)	0.379	0.44
ISq_{90}	4	18 (7)	10 (8)	-8 (4)	0.026	2.03

Table 22 – Inter-limb asymmetry response in the unilateral strength training group. SI score = symmetry index score, BIL = bilateral training group, UNI = unilateral training group. Δ = change in SI score. Note that positive Δ values indicate that asymmetry increased, negative Δ values indicate that asymmetry decreased.

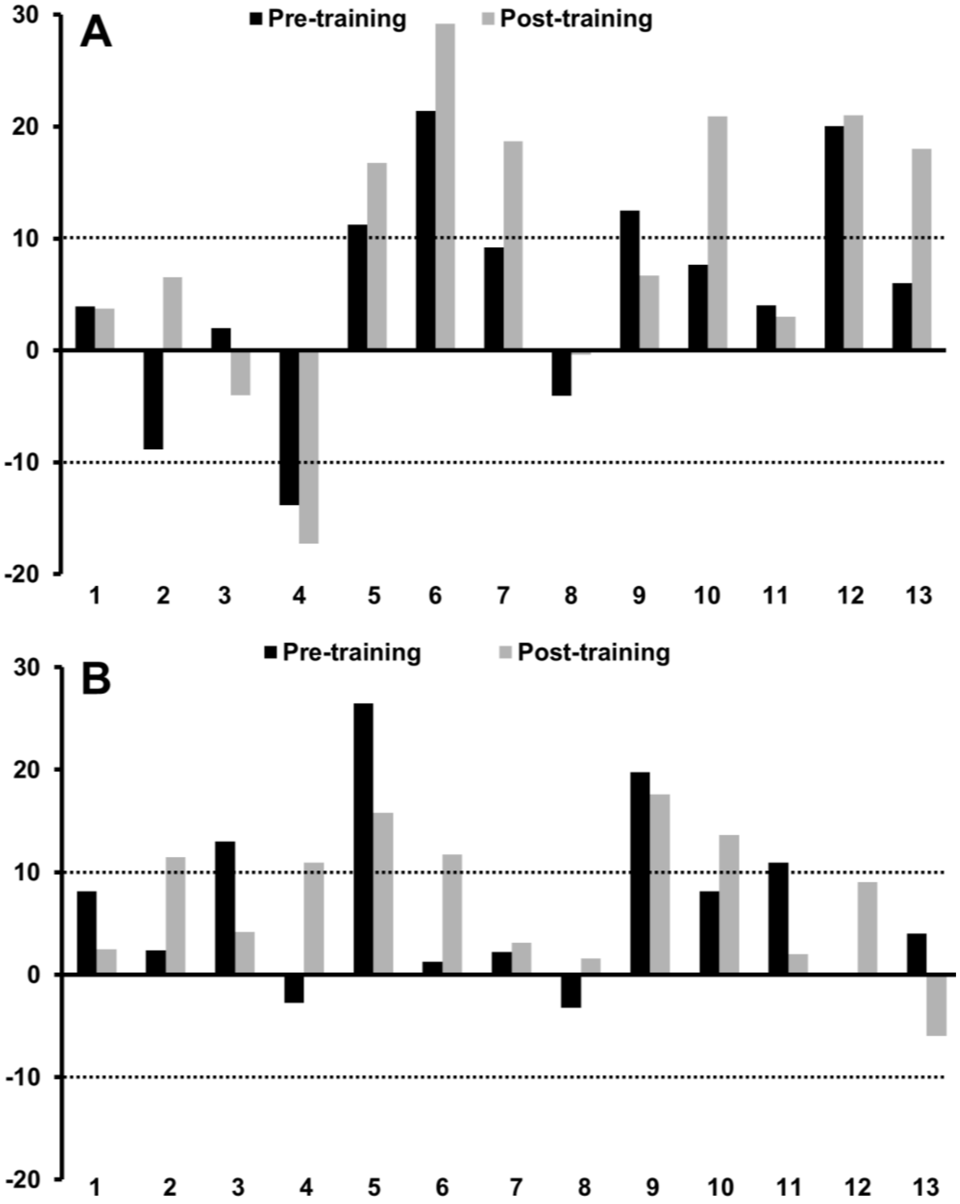

Figure 23 - Individual asymmetry data for isometric squat peak force in subjects who performed unilateral strength training (n = 13). **A** represents data from the ISq_{120}, **B** represents data from ISq_{90}. Black bars represent values pre-training, grey bars represent values post-training. Positive values indicate stronger right side, negative values indicate a stronger left side. Dashed line indicates the ≥ 10 % SI score cut-off.

	ISq_{120}	ISq_{90}	1RM
Baseline [Mean (SD)]	1687.1 (612.1) N	1045.0 (229.2) N	100.2 (25.2) kg
Post-training [Mean (SD)]	1840.2 (610.0) N	1054.6 (221.2) N	110.5 (22.4) kg
Change [Mean (SD)] %	11.4 (19.1) %	2.0 (14.0) %	11.8 (10.0) %
[95% CI] Δ	[-23.6, 329.8] N	[-71.2, 90.5] N	[5.4, 15.4] kg
[95% CI] %	[-1.4, 19.5] %	[-6.8, 8.7] %	[5.4, 15.4] %
P	0.08	0.8	0.001
d	0.5	0.1	1.3

Table 23 - Maximal strength changes following unilateral training. [95% CI] = 95 % confidence interval, Δ = change (absolute value).

4. Comparison of the effects of bilateral vs. unilateral strength training on changes in inter-limb asymmetry in PIF among subjects with ≥ 10 % SI scores at baseline

Based on data from the sub-groups that presented with ≥ 10 % SI scores at baseline, reductions in SI scores between groups were significantly greater in the bilateral training group at ISq_{120} (bilateral group SI score change = -6 (4), unilateral group SI score change = 2(5); $P = 0.015$), with no between-group differences at ISq_{90} (bilateral group SI score change = -5(5), unilateral group SI score change = -8(4); $P = 0.373$).

5. The influence of asymmetry reduction on changes in performance

Regression analyses of the changes in SI score, plotted against changes in performance amongst the sub-groups (≥ 10 % SI scores at baseline) were not significant ($R^2 \leq 0.723$, $P \geq 0.106$) and these are displayed in Figures 24 and 25.

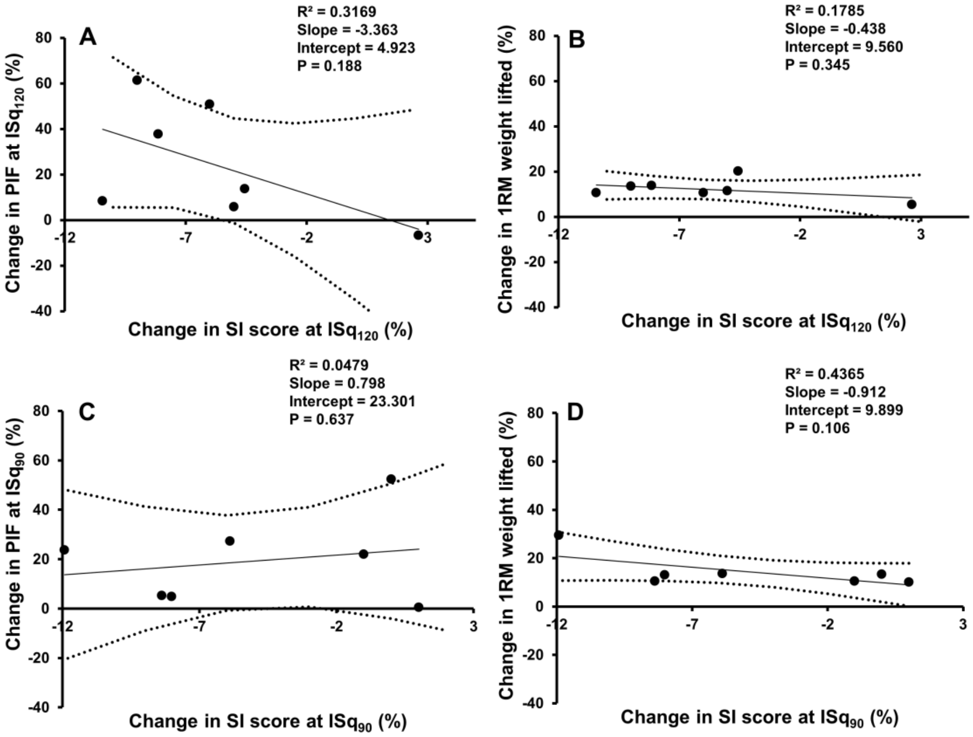

Figure 24 – Regression analyses for changes in SI scores (x-axis) against changes in performance (y-axis) in subjects who presented with SI scores of ≥ 10 % at baseline and performed bilateral strength training. **A** represents changes in SI scores at ISq_{120} against changes in peak force at ISq_{120}, **B** represents changes in SI scores at ISq_{120} against changes in 1RM, **C** represents changes in SI scores at ISq_{90} against changes in peak force at ISq_{90}, **D** represents changes in SI scores at ISq_{90} against changes in 1RM. Dashed lines represent the 95 % confidence intervals.

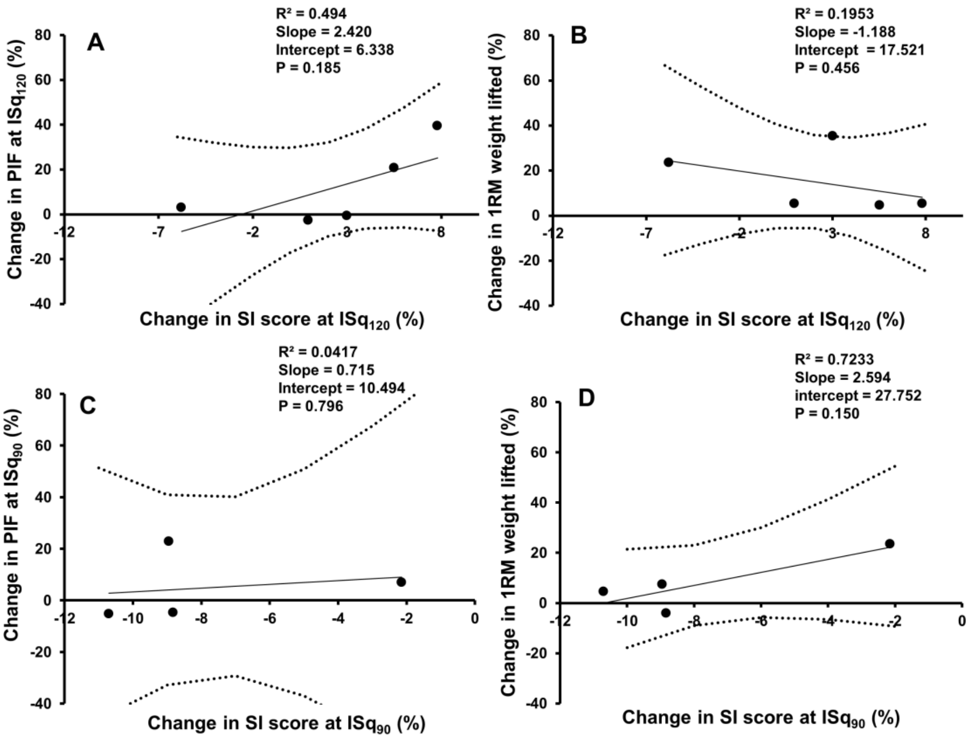

Figure 25 – Regression analyses for changes in SI scores (x-axis) against changes in performance (y-axis) in subjects who presented with SI scores of ≥ 10 % at baseline and performed unilateral strength training. **A** represents changes in SI scores at ISq_{120} against changes in peak force at ISq_{120}, **B** represents changes in SI scores at ISq_{120} against changes in 1RM, **C** represents changes in SI scores at ISq_{90} against changes in peak force at ISq_{90}, **D** represents changes in SI scores at ISq_{90} against changes in 1RM. Dashed lines represent the 95 % confidence intervals.

6.5 Discussion

The objective of this study was to examine the use of the ISq to detect and monitor changes in inter-limb asymmetries in PIF. Initial observation of the inter-limb asymmetry phenomenon was made in study 1 (Chapter 3). This sparked inquiry into the use of the ISq for studying inter-limb asymmetry. Firstly, inter-limb asymmetries were detected amongst volunteers for study

2 (Chapter 4) and these are summarised in Table 20. A noteworthy finding in this part of the investigation was that of the 59 subjects in this cohort, as many as 18 subjects presented with an inter-limb asymmetry that was ≥ 10 %, based on SI scores (Table 20). Further investigation was sought following these results. The next phase of the study aimed to investigate the potential impact of strength training on inter-limb asymmetries in strength, which could then be determined using the ISq. Specifically, the effects of a 6 week bilateral strength training program, performed twice per week on inter-limb asymmetries in the ISq_{120} and ISq_{90} were assessed. Overall, when analysis was performed on all subjects (n = 18), the inter-limb asymmetry responses to training were highly variable (see Figure 22) and changes were not significant (Table 21). However, when a sub-analysis of subjects who presented with ≥ 10 % SI scores at baseline, significant reductions in SI scores were observed at both ISq_{120} ($P = 0.001$, $d = 1.35$, n = 7) and ISq_{90} ($P = 0.039$, $d = 0.99$, n = 7). This reduction in ISq measured SI scores following bilateral training was a noteworthy finding, one which replicates the findings of (Bazyler *et al*. (2014). Therefore, the final component of this study was to examine the effects of a different training protocol on inter-limb asymmetries in ISq measured PIF. Subjects (n = 13) performed 6 weeks of unilateral strength training (repetition and effort matched with that of the bilateral training group), with inter-limb asymmetries in PIF as well as maximal strength measures (ISq_{120}, ISq_{90} and 1RM back squat) assessed pre and post-training. Indirect evidence from previous studies suggested that unilateral training protocol would be effective for asymmetry reduction (Brown *et al*. 2017; Gonzalo-Skok *et al*. 2017) as well as 1RM back squat performance (Speirs *et al*. 2016).

In a similar vein to the bilateral training group, when analysis was performed on all subjects, the inter-limb asymmetry responses to training were highly variable (see Figure 23) and changes were not significant (Table 22). However, in the sub-group of subjects who presented with marked asymmetries (≥ 10 % SI scores at baseline), the results showed that unilateral strength training was effective at reducing inter-limb asymmetries at ISq_{90}, but not at ISq_{120} (Table 22). This position specific asymmetry response is somewhat difficult to explain. Broadly speaking, inter-limb asymmetries are highly task specific (Bishop *et al*. 2020), which may help to explain this finding. To further evidence this point, consider the number of subjects who presented with baseline SI scores of ≥ 10 % in Tables 20 and 22. Of the 59 subjects in Table 20, 18 presented with SI scores of ≥ 10 % at ISq_{120}, with only 14 at ISq_{90}. Similarly, 5 of the 13 subjects in Table 22 presented with SI scores of ≥ 10 % at ISq_{120}, whereas 4 presented with SI scores of ≥ 10 % at ISq_{90}. Overall, this highlights that even within the same test; simply adjusting the position (i.e. ISq_{120} vs. ISq_{90}) can affect the presence of inter-limb asymmetry. This highly specific nature of the inter-limb asymmetry phenomenon must be considered when interpreting an observed asymmetry in a particular test. Practically speaking, the results presented herein suggest that practitioners ought to assess and interpret asymmetry scores on an individual basis.

It is speculated that the results may have been different if all subjects were able to complete the intervention. The ≥ 10 % cut-off was chosen as this has previously shown associations with increased injury risk as well as reduced performance (Bell *et al*. 2014; Bishop *et al*. 2018a) and therefore could theoretically be considered meaningful. In addition, ≥ 10 % is outside the mean error associated with assessment of peak force in the ISq_{120} and ISq_{90}

(~ 8.1 % CV). Reporting of inter-limb asymmetries in conjunction with the typically observed variability of the test may help to differentiate the signal from the noise inherent with any performance test (Bishop *et al*. 2020).

To the author's knowledge, this is the first study to investigate the effects of unilateral strength training on changes in PIF in the ISq. Following the unilateral strength training intervention increases in PIF did not reach significance at either ISq_{120} or ISq_{90} (Table 23), though if all subjects who enrolled in the study were able to complete the intervention it is conceivable that the increases in PIF at ISq_{120} could have reached significance ($P = 0.08$, $d = 0.5$). Unfortunately, 7 subjects were unable to complete the study due to restrictions imposed by the Covid 19 pandemic. Nonetheless, when changes in PIF resulting from the unilateral training program are compared to that of the bilateral training program (see Table 16 of Chapter 5), superior results were observed in the bilateral training group. A possible explanation for this may be the greater specificity between the exercises used in the bilateral training program (back squat and deadlift) with the ISq, which is performed bilaterally. By contrast, increases in 1RM back squat weight lifted in the unilateral training group were significant (Table 23) and comparable with that of the bilateral training group (Table 16, Chapter 5). This was not an unexpected finding, as unilateral strength training using the rear foot elevated split squat has previously been shown to increase 1RM back squat following a 5 week training intervention (Spiers *et al*. 2016).

In the current study, both forms of training were effective at achieving reductions in SI scores of ≥ 10 % at baseline in the ISq_{90}, although only the bilateral training demonstrated an effect at ISq_{120} (Table 21, Table 22). This runs somewhat contrary to previous training studies. Gonzalo-Skok *et al*.

(2017) compared the effects of bilateral vs. unilateral training on performance and inter-limb asymmetries in strength, concluding that whilst both were effective for improving performance, only unilateral training was effective at reducing inter-limb asymmetries. It is worth considering that in the Gonzalo-Skok *et al*. (2017) study not only were mean asymmetries in the unilateral training group greater (9.6 %) at baseline compared to the bilateral training group (6.9 %), but also that asymmetries were determined using the rear foot elevated split squat (RFESS). Whilst the RFESS has previously been shown to be a valid and reliable test of asymmetry (Helme *et al*. 2019), it is unclear how the results of this test would compare to that of the ISq. To the author's knowledge, asymmetries in the RFESS and ISq have not been compared within the same group of individuals, but results from the IMTP show rather large differences in the magnitude of asymmetry in the bilateral and unilateral versions of this test (24 % vs. 10 % asymmetry respectively), within the same group of individuals (Kuki *et al*. 2019). This highlights the difficulty in comparing across studies that use different performance tests to assess asymmetry, particularly between unilateral and bilateral tests.

Prior to commencing the study, it was believed that any reductions in asymmetry would be reflected by increases in performance. In other words, it was hypothesized that there would be a positive relationship between reductions in asymmetry and increases in performance in the 1RM and/or the ISq. This was largely based on the theoretical framework proposed by Maloney (2019), whereby a performance deficit between limbs presents a potential adaptation window of opportunity, and a reduction in this asymmetry would increase the overall performance (assuming performance of the stronger limb remains unchanged). Bazyler *et al*. (2014) provides some support for this theory. In their study, a group of 16 recreationally trained males were divided into 'stronger' and 'weaker' sub-groups based on their ISq peak force data at baseline. Greater SI scores at ISq_{120} and ISq_{90} were observed in weaker compared to stronger individuals at baseline, which were significantly reduced following training. Both sub-groups significantly improved 1RM as well as peak force at ISq_{120} and ISq_{90}, with no differences between groups. Whilst performance increases in the weaker sub-group did not out-perform that of the stronger sub-group, an inverse relationship was observed between SI scores at ISq_{120} and peak force at ISq_{120}. ($r = -0.64$, $P = 0.004$). This equates to an R^2 value of 0.41. Using the data from the two sub-groups (≥ 10 % SI scores at baseline) from the current study, regression analyses were performed for changes in inter-limb asymmetry and changes in performance (ISq_{120}, ISq_{90} and 1RM). These are displayed in Figures 24 and 25 for the bilateral and unilateral training groups respectively). The results somewhat support the findings of Bazyler *et al*. (2014). The strongest relationships were observed between changes in SI scores at ISq_{90} and changes in PIF at ISq_{90} for both the bilateral ($R^2 = 0.437$) and the unilateral training groups ($R^2 = 0.723$). Whilst neither of these reached statistical significance ($P \geq 0.150$), this may be related to the small sample size of the current study, which in turn limits the overall ability to extrapolate these results. The relationship may have been stronger if the sample size was increased. It is worth noting that of the 7 subjects lost during the training phase due to restrictions imposed by the Covid 19 pandemic, 5 of these presented with a baseline asymmetry of ≥ 10 % at either ISq_{120}, ISq_{90} or both.

6.6 Conclusions and practical applications

The data reported in this Chapter highlight the utility of the ISq to detect and monitor inter-limb asymmetries in PIF. In addition, the results provide evidence for the efficacy of both bilateral and unilateral strength training to reduce inter-limb asymmetries in ISq measured PIF in a population of uninjured, moderately strength trained males. Whilst statistical power was ultimately thwarted by subject dropout (due to unforeseen circumstances imposed by the 2020 Covid-19 pandemic), the results serve to reiterate the highly specific nature of inter-limb asymmetry assessment. Overall, meaningful inter-limb asymmetries in ISq measured PIF appear to be attenuated as a by-product of the response to strength-training, at least amongst uninjured individuals who are moderately strength trained. Practically speaking, both forms of training are effective at increasing 1RM performance in this population, which provides practitioners with greater scope when it comes to exercise selection for improving performance. Specificity, personal preference and/or any physical limitations that an individual may have should all be considered in the exercise selection process in this context. Much of the overall relevance of inter-limb asymmetries remains unclear, though it appears that bilateral strength training may be the more effective option for reducing asymmetries in the ISq.

Chapter 7

7.0 Main findings

This thesis sought to examine the use of the ISq as a measure of maximal strength, focusing on the utility of different ISq positions, the reliability of the measure, the sensitivity of the measure to training induced changes in maximal strength as well as the application of the ISq to detect and monitor inter-limb asymmetries.

The main findings of this thesis are as follows:

1. The ISq demonstrates acceptable levels of reliability when performed at a 120°, 90° and 65° knee angle for PIF, but not for RFD.
2. The previously unexplored ISq_{65} position produces comparable reliability scores to that of more established ISq_{120} and ISq_{90} positions, though substantially lower PIF is produced in this position.
3. Reliability of PIF in the ISq is not influenced by maximal strength level, though it appears that the reliability of the measure may be greatest in more highly strength trained individuals.
4. The ISq is sensitive to training induced changes in maximal strength.
5. The ISq is capable of detecting inter-limb asymmetries in PIF at ISq_{120} and ISq_{90}.
6. Strength training can attenuate ISq measured inter-limb asymmetries in ISq measured PIF at ISq_{120} and ISq_{90}.

7.1 Discussions and practical applications

7.1.1 The influence of squat position on the reliability of isometric squat force variables

In Chapter 3, the reliability of PIF and RFD in the ISq were investigated at a 120° and 90° knee angle, as well as a previously unexplored 65° knee angle. In the conduct of ISq testing (as well as the instructions given to the subjects), the primary objective was that of obtaining the greatest and most reliable data for PIF (to the likely detriment of RFD data) as the focus of this thesis was maximal strength assessment. The results reflect this methodological choice, with greater reliability observed for PIF compared to RFD. All between-day variables achieved the pre-determined reliability thresholds (CV < 10 %, ICC ≥ 0.8), whilst some variables fell outside these thresholds for within-day reliability. Practically speaking, between-day reliability is of greatest relevance to the monitoring of performance change over time (Hopkins 2000). By contrast, the majority of RFD variables fell outside the reliability thresholds. In addition, recent evidence from Drake *et al*. (2019) suggests that separate test procedures ought to be conducted independently for obtaining optimal PIF and RFD data respectively. The former corresponds with the procedures used within this thesis; the latter involves a 1 s contraction with different instructions given to subjects, the primary aim of which being the production of the highest force as fast as possible, thereby maximizing RFD. Using these procedures, both RFD values and their reliability were improved (Drake *et al*. 2019). Taking into account these findings, as well as the observation of poor reliability of the RFD measurement in the current study, this is why the proceeding studies did not document RFD data. In addition, this was the only study that assessed the reliability of PIF at ISq_{65}. The reason for not continuing to use this position was not due to a lack of observed reliability, but rather based on subject feedback. Given the mobility demands of the position, some subjects had difficulty attaining the required positioning, particularly those with less training experience, which may have affected the quality of the PIF data. However, those who were of a higher training status did not have the same difficulty achieving the ISq_{65} position. In addition the reliability of PIF in the ISq_{65} was comparable with ISq_{120} and ISq_{90}, suggesting that practitioners and future investigators can use this position, though it may be more appropriate to do so in well-trained individuals, or rather in strength athletes (i.e. Powerlifters and Olympic Weightlifters) where force production in this position is of great relevance to performance.

In contrast with the isometric mid-thigh pull (IMTP), where it is recommended to perform the test in an upright position with a knee angle of 125-145°, the ISq can be performed across a variety of positions, depending on the application of the testing. ISq positions performed closer to full knee extension (120-140°) require minimal skill and mobility and produce greater peak forces. Contrastingly, lower ISq positions ($\leq 90°$ knee angle) may be of greater relevance to dynamic strength performance, or in sports that require deep squatting positions with a prerequisite level of strength.

7.1.2 Reliability of the isometric squat force output in subjects of varying levels of strength and training status

As outlined in the Chapter 1, the reliability of maximal strength assessments can be population specific. With regards to the 1RM back squat, the reliability of this test does appear to improve with increased subject strength training experience (and therefore overall strength level). Conversely, the relationship between training status and ISq reliability was a previously unexplored one. This was the focus of Chapter 4. The results of this investigation suggest no relationship between strength (as indicated by PIF values) and the between-day reliability of PIF measurement (based on CV data) at either ISq_{120} or ISq_{90}.

When subjects were divided into sub-groups based on their training status at the time of study enrolment, between-day CV decreased as a function of training status (i.e. CV of untrained > moderately trained > highly trained). This may be related to a greater familiarity with maximal effort contractions amongst the more highly trained individuals. However, it is important to note that the differences in CV between sub-groups were not significant. As a rebuttal to this point, the lack of significant differences between the sub-groups may be related to disparity in numbers between the untrained (n = 8), moderately trained (n = 42) and highly trained (n = 9) sub-groups. Interestingly, mean PIF values for the moderately trained sub-group did not differ from that of the highly trained sub-group at either ISq_{120} or ISq_{90}, despite substantial differences in training experience and 1RM back squat strength between these sub-groups. In this context, both sub-groups were naïve to the specifics of the ISq test, which may help to explain the lack of differences between sub-groups for PIF (Buckner *et al*. 2017). This highlights the specific nature of both the ISq and the 1RM tests. Whilst the two are biomechanically quite similar, ultimately they are still two different tests.

Overall the data presented in Chapter 4 indicate that the reliability of the ISq is not readily influenced by the maximal strength or training status of an individual. Similar findings have been observed for the IMTP (Beckham *et al*. 2018), although this is the first study to report such findings for the ISq. A similar study does not exist for the 1RM back squat. However, by comparing studies from different populations, it appears the reliability of this test may be influenced by the training status of an individual, with reliability improving with increased training status (Nuzzo *et al.* 2019). For researchers and practitioners, the data presented here suggest the ISq is an appropriate test of maximal strength that can be used across populations of differing levels of strength and training status.

7.1.3 The sensitivity of the isometric squat test to detect training induced changes in maximal strength

Study three (Chapter 5) may carry the most overall practical relevance to practitioners and sport science researchers who use the ISq. In this study, the sensitivity of the ISq_{120} and ISq_{90} to strength training induced changes in strength was investigated. Significant increases in all outcome measures (PIF in the ISq_{120} and ISq_{90} as well as 1RM weight lifted) were observed following training. Mean changes were greater than the TE value for ISq_{120}, ISq_{90} and 1RM. However, observed changes in the ISq_{120} and ISq_{90} displayed much greater variability around the mean compared to the 1RM. It is speculated that this may be due to the greater specificity between the back squat (which was the primary training exercise) and the 1RM back squat test, compared to the ISq_{120}, ISq_{90}. The frequent exposure to the back squat exercise as part of the training intervention likely facilitated motor learning, whereby an individual learns to produce the specific patterns of muscle recruitment necessary for improved performance in that movement (Carroll *et al*. 2001). By contrast, when the ISq is performed as part of the training intervention, more robust increases in ISq measured PIF (i.e. similar to the mean increases reported in Chapter 5, but with less variability around the mean) have been observed (Lum and Joseph 2019). The more homogenous results of Lum and Joseph (2019) compared to the varied responses observed here support the prior interpretation that the degree of specificity between the training exercise and the performance test likely influenced the results. As a rebuttal to this point, similar increases in 1RM back squat strength were observed in the unilateral strength training group (Chapter 6) compared to the bilateral strength training group (11.8 % vs. 13.6 % increase for unilateral and bilateral groups respectively) despite no back squat exercise being performed as part of the training intervention. This suggests some degree of generality in the adaptation. Ultimately, like all performance based tests within sport science, it is difficult to dissociate improved performance from specificity with the test (Buckner *et al*. 2017).

Overall, whilst it is concluded that the ISq is sensitive to detect training induced changes in ISq measured PIF following a 6 week bilateral strength training intervention, the 1RM does appear to display superior reliability and sensitivity (as well as being more practically accessible). However, researchers and practitioners may wish to use the ISq as an outcome measure depending on the context of the performance test. The characteristics of the ISq may be more appealing to researchers and/or practitioners compared to the 1RM; namely the ability to standardise the position, overcoming any potential safety concerns in the conduct of the 1RM (e.g. a subject falling, potential injury to a spotter if the bar is dropped etc.) and the length of time needed to conduct the test (under 30 min allowing for a 5 min warm up, up to 6 min for submaximal warm up trials and up to 15 min for 3 the maximal effort trials + 3 min rest periods in between). By contrast, 1RM testing can be much more time consuming, particularly when assessing highly trained individuals.

7.1.4 Attenuation of inter-limb asymmetry of force production in the isometric squat with strength training

Whilst the overall relevance of inter-limb asymmetries amongst non-injured individuals remains unclear, it seems plausible that marked asymmetries in ISq performance could be viewed as detrimental to overall performance of in-phase bilateral symmetric motor tasks (Maloney 2019). In addition to previous evidence demonstrating an attenuation of ISq measured inter-limb asymmetries following bilateral training (Bazyler *et al*. 2014), attenuation of inter-limb asymmetry in ISq measured PIF was observed following study 3 (Chapter 5), which motivated further inquiry into the effects of strength training on inter-limb asymmetry. To date, no study had previously investigated the effects of unilateral strength training on inter-limb asymmetries in PIF in the ISq. Consequently, the aim of this study was to examine the inter-limb asymmetry response to 6 weeks to unilateral strength training (using the rear foot elevated split squat and single leg deadlift). In those who presented with marked asymmetry at baseline (defined as ≥ 10 % SI score), associations between reductions in inter-limb asymmetry and changes in performance in either the ISq or the 1RM were also assessed.

Overall, the asymmetry response to unilateral strength training was highly variable, with no significant effects on SI scores observed at either ISq_{120} when all subjects were analysed as part of their respective training groups.

By contrast, when a sub-analysis of subjects with baseline SI scores of ≥ 10 % was performed, significant reductions in SI scores were observed at ISq_{90}. When the results were compared to that of the bilateral training intervention, both training programs were effective at reducing inter-limb asymmetries in PIF at ISq_{90}, though only the bilateral training produced reductions in asymmetry at ISq_{120}. The reason for the lack of effect at ISq_{120} in the unilateral group is difficult to explain beyond concluding that bilateral strength training appears to be more effective for attenuating asymmetries in PIF. In addition, given the number of subjects in the sub-groups with baseline SI scores of ≥ 10 % at ISq_{120} (n = 5) and ISq_{90} (n = 4), any overall effects on asymmetries (either positive or no change) ought to be interpreted very cautiously.

Finally, in those subjects with ≥ 10 % baseline SI scores, no significant relationships were observed between changes in SI scores and any of the performance outcomes (1RM, ISq_{120} or ISq_{90}) following training. This latter finding casts some doubt on the overall practical relevance of asymmetry attenuation as it relates to performance. However, having lost a number of subjects due to restrictions imposed by the Covid 19 pandemic, it is a possibility that the results may have differed if all subjects had been brought to completion of the intervention. For greater context, 5 of the 7 subjects lost due to the pandemic restrictions had a baseline SI score of ≥ 10 % at either ISq_{120} and/or ISq_{90}. Future research is required to help elucidate this phenomenon. In summary, both bilateral and unilateral strength training can be effective at reducing inter-limb asymmetries in PIF in the ISq, in those with ≥ 10 % inter-limb asymmetry in PIF, though it appears that bilateral training might be more effective overall. For the purpose of improving 1RM back squat weight lifted in this population, both training modalities can be effective. For the purpose of improving PIF in the ISq, bilateral strength training appears to produce superior results.

The results of study four (Chapter 6) highlight the utility of the ISq in detecting inter-limb asymmetries in maximal strength as well as monitoring of such asymmetries in response to training, supporting previous use of the ISq in this application. In contrast with the findings of Bazyler *et al*. (2014) reductions in asymmetries were not associated with increases in performance in the ISq_{120}, ISq_{90} or 1RM. This is somewhat at odds with the narrative proposed in Chapter 1, whereby a meaningful asymmetry in PIF presents a potential adaptation 'window of opportunity' (Maloney 2019) that if attenuated, would be reflected in an increased performance (in this case, the sum of the PIF of the individual limbs ought to increase if the deficit between limbs is reduced). Reasons for the observed lack of a significant relationship between reductions in asymmetry and increases in performance are unclear but may be at least partly related to the rather small sample of individuals who presented with SI scores of ≥ 10 % at baseline and completed the entire intervention. Practically speaking, meaningful inter-limb asymmetries appear to be attenuated as a by-product of the response to strength-training, at least amongst uninjured individuals who are moderately strength trained. The highly specific nature of inter-limb asymmetry means that their overall relevance still remains somewhat unclear, a conclusion that has also been made elsewhere (Bishop *et al*. 2020).

7.2 Limitations

The work programme undertaken and documented within this thesis focused on the use of the ISq as a measure of maximal muscle strength. Following study one (Chapter 3), the decision was taken not to proceed with the ISq_{65}. This was done based on a number of reasons. Firstly, PIF was lowest in this position compared to the ISq_{120} and ISq_{90}. This was not an unexpected finding, as PIF ~~is~~ generally decreases with increased knee flexion (Palmer *et al*. 2017). However, when combined with the verbal feedback from subjects, who reported difficulty in attaining the position, it is possible that this affected the quality of the data for PIF. No such feedback was given for the ISq_{120} and ISq_{90}. As a result, despite the comparable reliability observed in this position, it was decided not to continue its use after study one. This means that the conclusions drawn about the sensitivity of the ISq to strength-training induced changes in 1RM can only be applied to the ISq_{120} and ISq_{90}. The TE value of 11 % in the ISq_{65} reported in study one provides researchers and practitioners with an indication of the change score necessary to be considered real in this position.

It was decided to focus this research exclusively on male subjects, given the inclination to maximize internal validity as exercise performance can fluctuate across the menstrual cycle (McNulty *et al*. 2020). This would not have been a concern for studies one and two; however it may have influenced the results of studies three and four, as variation in performance may confound changes in ISq performance post-training. Additionally, it may have been more difficult to recruit a similar number of moderately trained female subjects. Consequently, the findings presented here may not extrapolate to females of a similar training status, though current evidence suggests the lower body strength response to strength training is similar across sexes (Roberts *et al*. 2020). There is currently a paucity of isometric squat research on female subjects, with no training interventions using the ISq as an outcome measure and only two studies assessing the reliability of the ISq in a female cohort (Palmer *et al*. 2017; Brady *et al*. 2017). This may be an available avenue for future research projects. Potentially, if the effects of the menstrual cycle could be accounted for (e.g. by recruiting subjects habitually using an oral contraceptive or implant), then this may mitigate any influence of performance variation across the menstrual cycle.

In a similar vein to the sex-specific nature of these findings, the information relating the training induced responses of the ISq are specific to moderately trained individuals. It was decided to focus on this population for the purpose of this thesis because individuals from this population were competent with basic strength training technique and in particular, the back squat exercise. This was an important ethical consideration as the performance of 1RM back squat testing in an untrained population presented an unjustifiable risk to subject safety. Conversely, moderately-trained subjects still had much greater scope for strength performance increases compared to more highly trained individuals; particularly within the confines of a 6 week training intervention.

Whilst all subjects were instructed to keep a number of potentially confounding variables (e.g. dietary intake, other exercise training) constant throughout the length of the respective interventions, the onus was on the subject to comply and thus it was not well controlled.

The results of study four (Chapter 6) provide evidence for the ability of both bilateral and unilateral strength training to attenuate marked inter-limb asymmetries in PIF in the ISq, adding to the current knowledgebase on this topic (Bazyler *et al.* 2014). The superior results observed in the bilateral training group suggest this type of training is superior for reducing asymmetries in ISq measured PIF. When examining the results of those who presented with baseline SI scores of ≥ 10 %, this reduced the number of subjects in each sub-group (7 in the bilateral group, 5 in the unilateral group with SI scores of ≥ 10 % in at least one position). This limits the overall ability to extrapolate the results. However, it is important to note that the intention was to equate the number of subjects in each sub-group, but the restrictions imposed as a result of the pandemic meant that 7 subjects were unable to complete the training intervention. The severity and length of the restrictions meant it was not possible to continue the intervention. Notwithstanding, this does not invalidate the results reported here, but it is acknowledged as a limitation.

7.3 Conclusions and recommendations for future work

The ISq demonstrated comparable reliability for PIF across three distinct ISq positions, indicating that the ISq is appropriate to use at each of these angles. Conversely, separate testing procedures are recommended for obtaining reliable data for RFD in the ISq. Researchers may wish to explore the use of the ISq_{65} as an outcome measure in future strength training interventions, given that the reliability of PIF in this position is comparable with that of other, more established ISq positions. This position may carry more overall relevance to strength athletes (i.e. Olympic weightlifters and Powerlifters) compared to other athletes, as a prerequisite level of strength in this position is a performance requirement in these disciplines.

The reliability of PIF in the ISq does not appear to be influenced by the magnitude of an individual's PIF in the ISq, although superior reliability was observed in very highly strength trained individuals. Future research may wish to establish the reliability of PIF in the ISq across varying levels of strength and training experience in females, although the (limited) available studies of reliability for PIF in the ISq using subjects from female populations suggests the reliability of the measure is equivalent to that of male subjects (Brady *et al*. 2017; Palmer *et al*. 2017).

The ISq is sensitive to strength training induced changes in maximal strength; though it is not as sensitive to change as the 1RM back squat, at least based on the methodological approaches used here. Future research may be able to elucidate the specificity vs. generality of adaptations to the ISq, with early work in this area suggesting that not unlike 1RM, increases in ISq measured PIF are influenced by the specificity of the training protocol that is utilised. Additionally, given the acknowledged population specific nature of the results presented here, future research may wish to determine the overall sensitivity of the ISq to training induced changes in maximal strength in highly strength trained individuals. It would be interesting to see the results of such a study, particularly given the findings here in study 2 (Chapter 4) showing no differences in PIF between moderately strength trained and highly strength trained individuals.

Finally, the ISq is an effective test for detecting and monitoring inter-limb asymmetries in PIF. Additionally, strength training can reduce inter-limb asymmetries. Additional research in this area is required to more comprehensively determine the overall effectiveness of unilateral strength training for the purpose of reducing inter-limb asymmetries in ISq measured

PIF. Overall, using a variety of study methodologies, the data contained within this thesis adds to the knowledgebase on the utility and versatility of the ISq.

References

Abernethy, P., Wilson, G. and Logan, P. (1995) 'Strength and power assessment', *Sports Medicine*, 19(6), 401-417.

Alegre, L.M., Jiménez, F., Gonzalo-Orden, J.M., Martín-Acero, R. and Aguado, X. (2006) 'Effects of dynamic resistance training on fascicle lengthand isometric strength', *Journal of Sports Sciences*, 24(05), 501-508.

Amagliani, R.M., Peterella, J.K. and Jung, A.P. (2010) 'Type of encouragement influences peak muscle force in college-age women', *International Journal of Exercise Science*, 3(4), 165.

Andersen, L.L. and Aagaard, P. (2006) 'Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development', *European Journal of Applied Physiology*, 96(1), 46-52.

Andrade, C. (2018) ‘Internal, external, and ecological validity in research design, conduct, and evaluation’, *Indian Journal of Psychological Medicine*, 40(5), 498.

Appleby, B.B., Cormack, S.J. and Newton, R.U. (2020) 'Unilateral and bilateral lower-body resistance training does not transfer equally to sprint and change of direction performance', *The Journal of Strength & Conditioning Research*, 34(1), 54-64.

Arazi, H. and Asadi, A. (2013) 'One repetition maximum test increases serum indices of muscle damage and soreness in trained and untrained males', *Apunts. Medicina de l'Esport*, 48(178), 49-54.

Argus, C.K., Gill, N.D., Keogh, J.W., Hopkins, W.G. and Beaven, C.M. (2009) 'Changes in strength, power, and steroid hormones during a professional rugby union competition', The *Journal of Strength & Conditioning Research*, 23(5), 1583-1592.

Atkinson, G. and Nevill, A.M. (1998) 'Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine', *Sports Medicine*, 26(4), 217-238.

Baechle, T.R. and Earle, R.W. (2008) *Essentials of Strength Training and Conditioning*, 3rd ed., Champaign, Illinois: Human Kinetics.

Bailey, C., Sato, K., Alexander, R., Chiang, C.-Y. and Stone, M.H. (2013) 'Isometric force production symmetry and jumping performance in collegiate athletes', *Journal of Trainology*, 2(1), 1-5.

Baker, D., Wilson, G. and Carlyon, B. (1994) 'Generality versus specificity: a comparison of dynamic and isometric measures of strength and speed-strength', *European Journal of Applied Physiology and Occupational Physiology*, 68(4), 350-355.

Baker, D. and Nance, S. (1999) 'The relation between strength and power in professional rugby league players', *The Journal of Strength & Conditioning Research*, 13(3), 224-229.

Baltzopoulos, V. and Brodie, D. (1989) 'Isokinetic dynamometry', *Sports Medicine*, 8(2), 101-116.

Banyard, H.G., Nosaka, K. and Haff, G.G. (2017) 'Reliability and validity of the load–velocity relationship to predict the 1RM back squat', *The Journal of Strength & Conditioning Research*, 31(7), 1897-1904.

Bazyler, C.D., Abbott, H.A., Bellon, C.R., Taber, C.B. and Stone, M.H. (2015) 'Strength training for endurance athletes: theory to practice', *Strength & Conditioning Journal*, 37(2), 1-12.

Bazyler, C.D., Bailey, C.A., Chiang, C.-Y., Sato, K. and Stone, M.H. (2014) 'The effects of strength training on isometric force production symmetry in recreationally trained males', *Journal of Trainology*, 3(1), 6-10.

Bazyler, C.D., Beckham, G.K. and Sato, K. (2015) 'The use of the isometric squat as a measure of strength and explosiveness', *The Journal of Strength & Conditioning Research*, 29(5), 1386-1392.

Bazyler, C.D., Sato, K., Wassinger, C.A., Lamont, H.S. and Stone, M.H. (2014) 'The efficacy of incorporating partial squats in maximal strength training', *The Journal of Strength & Conditioning Research*, 28(11), 3024-3032.

Beckham, G.K., Lamont, H.S., Sato, K., Ramsey, M.W. and Stone, M.H. (2012) 'Isometric strength of powerlifters in key positions of the conventional deadlift', *Journal of Trainology*, 1(2), 32-35.

Beckham, G.K., Sato, K., Santana, H.A., Mizuguchi, S., Haff, G.G. and Stone, M.H. (2018) 'Effect of body position on force production during the isometric midthigh pull', *The Journal of Strength & Conditioning Research*, 32(1), 48-56.

Bell, D.R., Sanfilippo, J.L., Binkley, N. and Heiderscheit, B.C. (2014) 'Lean mass asymmetry influences force and power asymmetry during jumping in collegiate athletes', *Journal of Strength and Conditioning Research*, 28(4), 884-891.

Bennell, K., Wajswelner, H., Lew, P., Schall-Riaucour, A., Leslie, S., Plant, D. and Cirone, J. (1998) 'Isokinetic strength testing does not predict hamstring injury in Australian Rules footballers', *British Journal of Sports Medicine*, 32(4), 309-314.

Benton, M.J., Raab, S. and Waggener, G.T. (2013) 'Effect of training status on reliability of one repetition maximum testing in women', *The Journal of Strength & Conditioning Research*, 27(7), 1885-1890.

Bishop, C., Read, P., Chavda, S. and Turner, A. (2016) 'Asymmetries of the lower limb: The calculation conundrum in strength training and conditioning', *Strength & Conditioning Journal*, 38(6), 27-32.

Bishop, C., Turner, A., Jarvis, P., Chavda, S. and Read, P. (2017) 'Considerations for selecting field-based strength and power fitness tests to measure asymmetries', *The Journal of Strength & Conditioning Research*, 31(9), 2635-2644.

Bishop, C., Turner, A. and Read, P. (2018a) 'Effects of inter-limb asymmetries on physical and sports performance: a systematic review', *Journal of Sports Sciences*, 36(10), 1135-1144.

Bishop, C., Lake, J., Loturco, I., Papadopoulos, K., Turner, A.N. and Read, P. (2018b) 'Interlimb asymmetries: The need for an individual approach to data analysis', *Journal of Strength and Conditioning Research*, June, 1-21.

Bishop, C., Read, P., Lake, J., Chavda, S. and Turner, A. (2018c) 'Interlimb asymmetries: understanding how to calculate differences from bilateral and unilateral tests', *Strength & Conditioning Journal*, 40(4), 1-6.

Bishop, C., Read, P., Lake, J.P., Loturco, I., Dawes, J., Madruga, M., Romero-Rodriguez, D., Chavda, S. and Turner, A. (2019) 'The unilateral isometric squat: Test reliability, inter-limb asymmetries, and relationships with limb dominance', *Journal of Strength and Conditioning Research*, February, 1-9.

Bishop, C., Read, P., Chavda, S., Jarvis, P., Brazier, J., Bromley, T. and Turner, A. (2020) 'Magnitude or Direction? Seasonal variation of interlimb asymmetry in Elite Academy Soccer Players', *Journal of Strength and Conditioning Research*, March, 1-7.

Bland, J. and Altman, D. (1990) 'A note on the use of the intraclass correlation coefficient in the evaluation of agreement between two methods of measurement', *Computers in Biology and Medicine*, 20(5), 337-340.

Blazevich, A.J., Gill, N. and Newton, R.U. (2002) 'Reliability and validity of two isometric squat tests', *The Journal of Strength & Conditioning Research*, 16(2), 298-304.

Bogdanis, G.C., Papaspyrou, A., Souglis, A.G., Theos, A., Sotiropoulos, A. and Maridaki, M. (2018) 'Effects of two different half-squat training programs on fatigue during repeated cycling sprints in soccer players', *Journal of Strength & Conditioning Research*, 25(7), 1849-1856.

Bolger, R., Lyons, M., Harrison, A.J. and Kenny, I.C. (2015) 'Sprinting performance and resistance-based training interventions: a systematic review', *Journal of Strength & Conditioning Research*, 29(4), 1146-1156.

Brady, C.J., Harrison, A.J., Flanagan, E.P., Haff, G.G. and Comyns, T.M. (2017) 'A comparison of the isometric midthigh pull and isometric squat: intraday reliability, usefulness, and the magnitude of difference between tests', *International Journal of Sports Physiology and Performance*, 13(7), 1-25.

Brady, C.J., Harrison, A.J. and Comyns, T.M. (2018) 'A review of the reliability of biomechanical variables produced during the isometric mid-thigh pull and isometric squat and the reporting of normative data', *Sports Biomechanics*, 19(1), 1-25.

Brady, C.J., Harrison, A.J., Flanagan, E.P., Haff, G.G. and Comyns, T.M. (2019) 'The relationship between isometric strength and sprint acceleration in sprinters', *International Journal of Sports Physiology and Performance*, 1(aop), 1-8.

Brown, S.R., Feldman, E.R., Cross, M.R., Helms, E.R., Marrier, B., Samozino, P. and Morin, J.-B. (2017) 'The potential for a targeted strength-training program to decrease asymmetry and increase performance: a proof of concept in sprinting', *International Journal of Sports Physiology and Performance*, 12(10), 1392-1395.

Bryanton, M.A., Kennedy, M.D., Carey, J.P. and Chiu, L.Z. (2012) 'Effect of squat depth and barbell load on relative muscular effort in squatting', *Journal of Strength & Conditioning Research*, 26(10), 2820-2828.

Buckner, S.L., Jessee, M.B., Mattocks, K.T., Mouser, J.G., Counts, B.R., Dankel, S.J. and Loenneke, J.P. (2017) 'Determining strength: a case for multiple methods of measurement', *Sports Medicine*, 47(2), 193-195.

Buckner, S.L., Kuehne, T.E., Yitzchaki, N., Zhu, W.G., Humphries, M.N. and Loenneke, J.P. (2019) 'The generality of strength adaptation', *Journal of Trainology*, 8(1), 5-8.

Buckthorpe, M.W., Hannah, R., Pain, T.G. and Folland, J.P. (2012) ‘Reliability of neuromuscular measurements during explosive isometric contractions, with special reference to electromyography normalization techniques’, *Muscle & Nerve*, 46(4), 566-576.

Campos, G.E., Luecke, T.J., Wendeln, H.K., Toma, K., Hagerman, F.C., Murray, T.F., Ragg, K.E., Ratamess, N.A., Kraemer, W.J. and Staron, R.S. (2002) 'Muscular adaptations in response to three different resistance-training regimens: specificity of repetition maximum training zones', *European Journal of Applied Physiology*, 88(1-2), 50-60.

Carroll, T.J., Riek, S. and Carson, R.G. (2001) ‘Neural adaptations to resistance training’, *Sports Medicine*, 31(12), 829-840.

Carroll, T.J., Selvanayagam, V.S., Riek, S. and Semmler, J.G. (2011) ‘Neural adaptations to strength training: moving beyond transcranial magnetic stimulation and reflex studies’, *Acta Physiologica*, 202(2), 119-140.

Carpinelli, R.N. (2011) 'Assessment of one repetition maximum (1RM) and 1RM prediction equations: Are they really necessary', *Medicina Sportiva*, 15(2), 91-102.

Carzoli, J.P., Sousa, C.A., Belcher, D.J., Helms, E.R., Khamoui, A.V., Whitehurst, M. and Zourdos, M.C. (2019) 'The effects of eccentric phase duration on concentric outcomes in the back squat and bench press in well-trained males', *Journal of Sports Sciences*, 37(23), 2676-2684.

Chavda, S., Turner, A.N., Comfort, P., Haff, G.G., Williams, S., Bishop, C. and Lake, J.P. (2020) 'A practical guide to analyzing the force-time curve of isometric tasks in Excel', *Strength & Conditioning Journal*, 42(2), 26-37.

Chelly, M.S., Fathloun, M., Cherif, N., Amar, M.B., Tabka, Z. and Van Praagh, E. (2009) 'Effects of a back squat training program on leg power, jump, and sprint performances in junior soccer players', *Journal of Strength & Conditioning Research*, 23(8), 2241-2249.

Choe, K.H., Coburn, J.W., Costa, P.B. and Pamukoff, D.N. (2018) 'Hip and Knee Kinetics during a Back Squat and Deadlift', *Journal of Strength and Conditioning Research*, 00(00), 1-8.

Cohen, J. (1988) 'Statistical power analysis for the behavioral sciences: Jacob Cohen', *Journal of the American Statistical Association*, 84(363), 19-74.

Comfort, P., Haigh, A. and Matthews, M.J. (2012) 'Are changes in maximal squat strength during preseason training reflected in changes in sprint performance in rugby league players?', *Journal of Strength & Conditioning Research*, 26(3), 772-776.

Comfort, P. and McMahon, J.J. (2015) 'Reliability of maximal back squat and power clean performances in inexperienced athletes', *Journal of Strength & Conditioning Research*, 29(11), 3089-3096.

Comfort, P., Dos' Santos, T., Beckham, G.K., Stone, M.H., Guppy, S.N. and Haff, G.G. (2019) 'Standardisation and methodological considerations for the isometric midthigh pull', *Strength & Conditioning Journal*, 41(2), 57-79.

Cormie, P., McCaulley, G.O. and McBride, J.M. (2007) 'Power versus strength-power jump squat training: influence on the load-power relationship', *Medicine & Science in Sports & Exercise*, 39(6), 996-1003.

Croisier, J.L., Ganteaume, S., Binet, J., Genty, M. and Ferret, J.M. (2008) 'Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study', *The American Journal of Sports Medicine*, 36(8), 1469-1475.

Cummins, M.E., Soomal, R.S. and Curtin, N.A. (1989) ‘Fatigue of isolated mouse muscle due to isometric tetani and tetani with high power output’, *Quarterly Journal of Experimental Physiology: Translation and Integration,* 74(6), 951-953.

Currell, K. and Jeukendrup, A.E. (2008) 'Validity, reliability and sensitivity of measures of sporting performance', *Sports Medicine*, 38(4), 297-316.

Davies, R.W., Carson, B.P., Bass, J.J., Holohan, S. and Jakeman, P.M. (2018) 'Acute reduction of lower-body contractile function following a microbiopsy of m. vastus lateralis', *Scandinavian Journal of Medicine & Science in Sports*, 28(12), 2638-2642.

Dello Iacono, A., Padulo, J. and Ayalon, M. (2016) 'Core stability training on lower limb balance strength', *Journal of Sports Sciences*, 34(7), 671-678.

Desaguliers J. (1763) Course of Experimental Philosophy. 3rd ed, London: Millar.

Dos' Santos, T., Lake, J., Jones, P.A. and Comfort, P. (2018) ‘Effect of low-pass filtering on isometric midthigh pull kinetics’, *Journal of Strength & Conditioning Research*, 32(4), 983-989.

Dos’Santos, T., Bishop, C., Thomas, C., Comfort, P. and Jones, P.A. (2019) 'The effect of limb dominance on change of direction biomechanics: a systematic review of its importance for injury risk', *Physical Therapy in Sport*, 37, 179-189.

Drake, D., Kennedy, R. and Wallace, E. (2017) 'The validity and responsiveness of isometric lower body multi-joint tests of muscular strength: A systematic review', *Sports Medicine-Open*, 3(1), 23.

Drake, D., Kennedy, R. and Wallace, E. (2018) 'Familiarization, validity and smallest detectable difference of the isometric squat test in evaluating maximal strength', *Journal of Sports Sciences*, 36(18), 2087-2095.

Drake, D., Kennedy, R.A. and Wallace, E.S. (2019) 'Multi-joint rate of force development testing protocol affects reliability and the smallest detectible difference', *Journal of Sports Sciences*, 37(14), 1570-1581.

Drid, P., Drapsin, M., Trivic, T., Lukač, D., Obadov, S. and Milosevic, Z. (2009) 'Asymmetry of muscle strength in elite athletes', *Biomedical Human Kinetics,* 1(2009), 3-5.

Ferri-Morales, A., Alegre, L.M., Basco, A. and Aguado, X. (2014) ‘Test-retest relative and absolute reliability of knee extensor strength measures and minimal detectable change’, *Isokinetics and Exercise Science*, 22(1), 17-26.

Folland, J.P., Mc Cauley, T.M. and Williams, A.G. (2008) ‘Allometric scaling of strength measurements to body size’, *European Journal of Applied Physiology*, 102(6), 739-745.

George, K., Batterham, A. and Sullivan, I. (2000) 'Validity in clinical research: a review of basic concepts and definitions', *Physical Therapy in Sport,* 1(1), 19-27.

Giavarina, D. (2015) ‘Understanding Bland Altman analysis.’, *Biochemia medica*, 25(2), 141-151.

Glassbrook, D.J., Helms, E.R., Brown, S.R. and Storey, A.G. (2017) 'A review of the biomechanical differences between the high-bar and low-bar back-squat', *Journal of Strength & Conditioning Research*, 31(9), 2618-2634.

Gonzalo-Skok, O., Tous-Fajardo, J., Suarez-Arrones, L., Arjol-Serrano, J., Casajus, J. and Mendez-Villanueva, A. (2015) 'Validity of the V-cut test for young basketball players', *International Journal of Sports Medicine*, 94(11), 893-899.

Gonzalo-Skok, O., Tous-Fajardo, J., Suarez-Arrones, L., Arjol-Serrano, J.L., Casajús, J.A. and Mendez-Villanueva, A. (2017) 'Single-leg power output and between-limbs imbalances in team-sport players: Unilateral versus bilateral combined resistance training', *International Journal of Sports Physiology and Performance*, 12(1), 106-114.

Grace, T., Sweetser, E., Nelson, M., Ydens, L. and Skipper, B. (1984) 'Isokinetic muscle imbalance and knee-joint injuries. A prospective blind study', *The Journal of Bone and Joint Surgery*, 66(5), 734-740.

Green, A., Tee, J. and McKinon, W. (2019) 'A review of the biomechanical determinants of rugby scrummaging performance', *South African Journal of Sports Medicine*, 31(1), 1-8.

Grgic, J., Trexler, E.T., Lazinica, B. and Pedisic, Z. (2018) 'Effects of caffeine intake on muscle strength and power: a systematic review and meta-analysis', *Journal of the International Society of Sports Nutrition*, 15(1), 11.

Grgic, J., Lazinica, B., Garofolini, A., Schoenfeld, B.J., Saner, N.J. and Mikulic, P. (2019) 'The effects of time of day-specific resistance training on adaptations in skeletal muscle hypertrophy and muscle strength: a systematic review and meta-analysis', *Chronobiology International*, 36(4), 449-460.

Grgic, J., Lazinica, B., Schoenfeld, B.J. and Pedisic, Z. (2020) 'Test–retest reliability of the one-repetition maximum (1RM) strength assessment: a systematic review', *Sports Medicine-Open*, 6(1), 1-16.

Guiard, Y. (1987) 'Asymmetric division of labor in human skilled bimanual action: The kinematic chain as a model', *Journal of Motor Behavior*, 19(4), 486-517.

Guppy, S.N., Brady, C.J., Kotani, Y., Stone, M.H., Medic, N. and Haff, G.G. (2019) 'Effect of altering body posture and barbell position on the within-session reliability and magnitude of force-time curve characteristics in the isometric midthigh pull', *Journal of Strength & Conditioning Research*, 33(12), 3252-3262.

Haff, G.G., Ruben, R.P., Lider, J., Twine, C. and Cormie, P. (2015) 'A comparison of methods for determining the rate of force development during isometric midthigh clean pulls', *Journal of Strength & Conditioning Research*, 29(2), 386-395.

Haff, G.G., Stone, M., O'Bryant, H.S., Harman, E., Dinan, C., Johnson, R. and Han, K.-H. (1997) 'Force-time dependent characteristics of dynamic and isometric muscle actions', *Journal of Strength & Conditioning Research*, 11(4), 269-272.

Hales, M.E., Johnson, B.F. and Johnson, J.T. (2009) 'Kinematic analysis of the powerlifting style squat and the conventional deadlift during competition: is there a cross-over effect between lifts?', *The Journal of Strength & Conditioning Research*, 23(9), 2574-2580.

Halperin, I., Pyne, D.B. and Martin, D.T. (2015) 'Threats to internal validity in exercise science: a review of overlooked confounding variables', *International Journal of Sports Physiology & Performance,* 10(7).

Harman, E. (1993) 'Strength and power: a definition of terms. *National Strength and Conditioning Association Journal*, 15(6), 18-20.

Hart, N., Nimphius, S., Wilkie, J. and Newton, R. (2012) 'Reliability and validity of unilateral and bilateral isometric strength measures using a customised, portable apparatus', *Journal of Australian Strength & Conditioning,* 20(1), 61-67.

Hart, N.H., Nimphius, S., Spiteri, T. and Newton, R.U. (2014) Leg strength and lean mass symmetry influences kicking performance in Australian Football, *Journal of Sports Science and Medicine,* 13(1), 157-165.

Hart, N.H., Newton, R.U., Weber, J., Spiteri, T., Rantalainen, T., Dobbin, M., Chivers, P. and Nimphius, S. (2020) 'Functional basis of asymmetrical lower-body skeletal morphology in professional australian rules footballers', *Journal of Strength & Conditioning Research*, 34(3), 791-799.

Hawley, J.A. (2008) 'Specificity of training adaptation: time for a rethink?', *Journal of Physiology*, 586(1), 1.

Helme, M., Bishop, C., Emmonds, S. and Low, C. (2019) 'Validity and Reliability of the Rear Foot Elevated Split Squat 5 Repetition Maximum to Determine Unilateral Leg Strength Symmetry', *The Journal of Strength & Conditioning Research*, 33(12), 3269-3275.

Hewit, J., Cronin, J. and Hume, P. (2012) 'Multidirectional leg asymmetry assessment in sport', *Strength & Conditioning Journal*, 34(1), 82-86.

Hodges, S.J., Patrick, R.J. and Reiser, R.F. (2011) 'Effects of fatigue on bilateral ground reaction force asymmetries during the squat exercise', *Journal of Strength & Conditioning Research*, 25(11), 3107-3117.

Hopkins, W.G. (2000) 'Measures of reliability in sports medicine and science', *Sports Medicine*, 30(1), 1-15.

Husted, J.A., Cook, R.J., Farewell, V.T. and Gladman, D.D. (2000) 'Methods for assessing responsiveness: a critical review and recommendations', *Journal of Clinical* Epidemiology, 53(5), 459-468.

Impellizzeri, F.M., Rampinini, E., Maffiuletti, N. and Marcora, S.M. (2007) 'A vertical jump force test for assessing bilateral strength asymmetry in athletes', *Medicine & Science in Sports & Exercise*, 39(11), 2044-2050.

Impellizzeri, F.M. and Marcora, S.M. (2009) 'Test validation in sport physiology: lessons learned from clinimetrics', *International Journal of Sports Physiology and Performance*, 4(2), 269-277.

IPF (2020) ‘IPF Technical Rules Book’, Luxembourg: Powerlifting.Sport.

Jaafar, H. and Lajili, H. (2018) 'The influence of verbal instruction on measurement reliability and explosive neuromuscular performance of the knee extensors', *Journal of Human Kinetics*, 65(1), 21-34.

Jones, P.A. and Bampouras, T.M. (2010) 'A comparison of isokinetic and functional methods of assessing bilateral strength imbalance', *Journal of Strength & Conditioning Research*, 24(6), 1553-1558.

Keiner, M., Sander, A., Wirth, K. and Schmidtbleicher, D. (2014) 'Long-term strength training effects on change-of-direction sprint performance', *Journal of Strength & Conditioning Research*, 28(1), 223-231.

Knapik, J.J., Bauman, C.L., Jones, B.H., Harris, J.M. and Vaughan, L. (1991) 'Preseason strength and flexibility imbalances associated with athletic injuries in female collegiate athletes', *The American Journal of Sports Medicine*, 19(1), 76-81.

Kobayashi, Y., Kubo, J., Matsuo, A., Matsubayashi, T., Kobayashi, K. and Ishii, N. (2010) 'Bilateral asymmetry in joint torque during squat exercise performed by long jumpers', *Journal of Strength & Conditioning Research*, 24(10), 2826-2830.

Kompf, J. and Arandjelović, O. (2017) 'The sticking point in the bench press, the squat, and the deadlift: Similarities and differences, and their significance for research and practice', *Sports Medicine*, 47(4), 631-640.

Koo, T.K. and Li, M.Y. (2016) 'A guideline of selecting and reporting intraclass correlation coefficients for reliability research', *Journal of Chiropractic Medicine*, 15(2), 155-163.

Kuki, S., Konishi, Y., Okudaira, M., Yoshida, T., Exell, T. and Tanigawa, S. (2019) 'Asymmetry of force generation and neuromuscular activity during multi-joint isometric exercise', *The Journal of Physical Fitness and Sports Medicine*, 8(1), 37-44.

Kushner, A.M., Brent, J.L., Schoenfeld, B.J., Hugentobler, J., Lloyd, R.S., Vermeil, A., Chu, D.A., Harbin, J., McGill, S.M. and Myer, G.D. (2015) ‘The back squat part 2: Targeted training techniques to correct functional deficits and technical factors that limit performance’, *Strength and Conditioning Journal*, 37(2), 13-60.

Lachin, J.M. (2004) 'The role of measurement reliability in clinical trials', *Clinical trials*, 1(6), 553-566.

Lamont, H.S., Cramer, J.T., Bemben, D.A., Shehab, R.L., Anderson, M.A. and Bemben, M.G. (2011) 'Effects of a 6-week periodized squat training with or without whole-body vibration upon short-term adaptations in squat strength and body composition', *Journal of Strength & Conditioning Research*, 25(7), 1839-1848.

Loturco, I., Pereira, L.A., Kobal, R., Zanetti, V., Gil, S., Kitamura, K., Abad, C.C.C. and Nakamura, F.Y. (2015) 'Half-squat or jump squat training under optimum power load conditions to counteract power and speed decrements in Brazilian elite soccer players during the preseason', *Journal of Sports Sciences*, 33(12), 1283-1292.

Loturco, I., Pereira, L.A., Abad, C.C.C., Gil, S., Kitamura, K., Kobal, R. and Nakamura, F.Y. (2016) 'Using bar velocity to predict maximum dynamic strength in the half-squat exercise', *International Journal of Sports Physiology and Performance*, 11(5), 697-700.

Loturco, I., Pereira, L.A., Kobal, R., Abad, C.C., Rosseti, M., Carpes, F.P. and Bishop, C. (2019) 'Do asymmetry scores influence speed and power performance in elite female soccer players?', *Biology of Sport*, 36(3), 209-216.

Lum, D. and Joseph, R. (2019) 'Relationship between isometric force-time characteristics and dynamic performance pre-and post-training', *The Journal of Sports Medicine and Physical Fitness*, December, 1-20.

MacKenzie, S.J., Lavers, R.J. and Wallace, B.B. (2014) 'A biomechanical comparison of the vertical jump, power clean, and jump squat', *Journal of Sports Sciences*, 32(16), 1576-1585.

Madruga-Parera, M., Bishop, C., Beato, M., Fort-Vanmeerhaeghe, A., Gonzalo-Skok, O. and Romero-Rodríguez, D. (2020) 'Relationship between interlimb asymmetries and speed and change of direction speed in youth handball players', *Journal of Strength & Conditioning Research*, May, 1-9.

Maloney, S.J. (2019) 'The relationship between asymmetry and athletic performance: A critical review', *Journal of Strength & Conditioning Research*, 33(9), 2579-2593.

Maffiuletti, N.A., Bizzini, M., Desbrosses, K., Babault, N. and Munzinger, U. (2007) 'Reliability of knee extension and flexion measurements using the Con-Trex isokinetic dynamometer', *Clinical Physiology and Functional Imaging*, 27(6), 346-353.

Maffiuletti, N.A., Aagaard, P., Blazevich, A.J., Folland, J., Tillin, N. and Duchateau, J. (2016) 'Rate of force development: physiological and methodological considerations', *European Journal of Applied Physiology*, 116(6), 1091-1116.

Marcora, S. and Miller, M.K. (2000) 'The effect of knee angle on the external validity of isometric measures of lower body neuromuscular function', *Journal of Sports Sciences*, 18(5), 313-319.

Markovic, G., Jukic, I., Milanovic, D. and Metikos, D. (2007) 'Effects of sprint and plyometric training on muscle function and athletic performance', *The Journal of Strength & Conditioning Research*, 21(2), 543-549.

McBride, J.M., Blow, D., Kirby, T.J., Haines, T.L., Dayne, A.M. and Triplett, N.T. (2009) 'Relationship between maximal squat strength and five, ten, and forty yard sprint times', *Journal of Strength & Conditioning Research*, 23(6), 1633-1636.

McBride, J.M., Skinner, J.W., Schafer, P.C., Haines, T.L. and Kirby, T.J. (2010) 'Comparison of kinetic variables and muscle activity during a squat vs. a box squat', *Journal of Strength & Conditioning Research*, 24(12), 3195-3199.

McGuigan, M.R., Winchester, J.B. and Erickson, T. (2006) 'The importance of isometric maximum strength in college wrestlers', *Journal of Sports Science & Medicine*, 5(CSSI), 108.

McGuigan, M.R., Newton, M.J., Winchester, J.B. and Nelson, A.G. (2010) 'Relationship between isometric and dynamic strength in recreationally trained men', *Journal of Strength & Conditioning Research*, 24(9), 2570-2573.

McLaughlin, T., Dillman, C. and Gardner, T. (1977) 'A kinematic model of performance in the parallel squat by champion powerlifters', *Medicine and Science in Sports*, 9(2), 128-133.

McMaster, D.T., Gill, N., Cronin, J. and McGuigan, M. (2014) 'A brief review of strength and ballistic assessment methodologies in sport', *Sports Medicine*, 44(5), 603-623.

McNulty, K.L., Elliott-Sale, K.J., Dolan, E., Swinton, P.A., Ansdell, P., Goodall, S., Thomas, K. and Hicks, K.M. (2020) 'The effects of menstrual cycle phase on exercise performance in eumenorrheic women: a systematic review and meta-analysis', *Sports Medicine*, 1-15.

Mills, B.S., McMaster, D.T. and Smith, B. (2019) 'Strength training recommendations to improve scrum force and impulse in rugby union forwards', *Strength & Conditioning Journal*, 41(1), 64-74.

Mitchell, C.J., Churchward-Venne, T.A., West, D.W., Burd, N.A., Breen, L., Baker, S.K. and Phillips, S.M. (2012) 'Resistance exercise load does not determine training-mediated hypertrophic gains in young men', *Journal of Applied Physiology*, 113(1), 71-77.

Möck, S., Hartmann. R., Wirth, K., Rosenkranz, G. and Mickel, C. (2018) ‘Relationship between maximal dynamic force in the deep back squat and sprinting performance in consecutive segments up to 30 m’, *Journal of Strength & Conditioning Research*, September, 1-5.

Moir, G.L., Getz, A., Davis, S.E., Marques, M. and Witmer, C.A., (2019) ‘The Inter-Session Reliability of Isometric Force-Time Variables and the Effects of Filtering and Starting Force’, *Journal of human kinetics*, 66(1), 43-55.

Murphy, A.J. and Wilson, G.J. (1997) ‘The ability of tests of muscular function to reflect training-induced changes in performance’, *Journal of Sports Sciences*, 15(2), 191-200.

Myer, G.D., Kushner, A.M., Brent, J.L., Schoenfeld, B.J., Hugentobler, J., Lloyd, R.S., Vermeil, A., Chu, D.A., Harbin, J. and McGill, S.M. (2014) ‘The back squat: A proposed assessment of functional deficits and technical factors that limit performance’, *Strength and Conditioning Journal*, 36(6), 4-27.

Newton, R.U., Häkkinen, K., Häkkinen, A., McCormick, M., Volek, J. and Kraemer, W.J. (2002) ‘Mixed-methods resistance training increases power and strength of young and older men’, *Medicine & Science in Sports & Exercise*, 34(8), 1367-1375.

Nuzzo, J.L., McBride, J.M., Cormie, P. and McCaulley, G.O. (2008) 'Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength', *Journal of Strength & Conditioning Research*, 22(3), 699-707.

Nuzzo, JL, Taylor, JL, and Gandevia, SC. (2019) ‘CORP: measurement of upper and lower limb muscle strength and voluntary activation’, *Journal of Applied Physiology*, 126(3), 513-543.

Oranchuk, D.J., Storey, A.G., Nelson, A.R., Neville, J.G. and Cronin, J.B. (2019) ‘Variability of multi-angle isometric force-time characteristics in trained men’, *Journal of Strength & Conditioning Research*, October 7.

Orchard, J., Marsden, J., Lord, S. and Garlick, D. (1997) 'Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers', *The American Journal of Sports Medicine,* 25(1), 81-85.

Owens, E.M. (2011) *Use of Isometric Mid-Thigh Pull to Determine Asymmetrical Strength Differences in NCAA DI Athletes* (MSc.), East Tennessee State University, available: https://dc.etsu.edu/etd/1370/.

Palmer, TB, Pineda, JG, and Durham, RM. (2017) ‘Effects of knee position on the reliability and production of maximal and rapid strength characteristics during an isometric squat test’, *Journal of Applied Biomechanics,* 34(2), 111-117.

Pearn, J. (1978) 'Two early dynamometers: an historical account of the earliest measurements to study human muscular strength', *Journal of the Neurological sciences*, 37(1-2), 127-134.

Pekünlü, E. and Özsu, İ. (2014) 'Avoiding systematic errors in isometric squat-related studies without pre-familiarization by using sufficient numbers of trials', *Journal of Human Kinetics*, 42(1), 201-213.

Peltonen, H. (2017) 'Isometric force-time parameters in monitoring of strength training: with special reference to acute responses to different loading resistances', *Studies in Sport, Physical Education and Health,* (264).

Pollock, M.L., Carroll, J.F., Graves, J.E., Leggett, S.H., Braith, R.W., Limacher, M. and Hagberg, J.M. (1991) 'Injuries and adherence to walk/jog and resistance training programs in the elderly', *Medicine and Science in Sports and Exercise*, 23(10), 1194-1200.

Pua, Y.-H., Bryant, A.L., Steele, J.R., Newton, R.U. and Wrigley, T.V. (2008) 'Isokinetic dynamometry in anterior cruciate ligament injury and reconstruction', *Annals Academy of Medicine Singapore*, 37(4), 330.

Renaud, J.M. and Kong, M. (1991) ‘The effects of isotonic contractions on the rate of fatigue development and the resting membrane potential in the sartorius muscle of the frog, Rana pipiens’, *Canadian Journal of Physiology and Pharmacology*, 69(11), 1754-1759.

Rhea, M.R., Alvar, B.A., Burkett, L.N. and Ball, S.D. (2003) 'A meta-analysis to determine the dose response for strength development', *Medicine and Science in Sports and Exercise*, 35(3), 456-464.

Ribeiro, A.S., do Nascimento, M.A., Salvador, E.P., Gurjão, A.L.D., Avelar, A., Ritti-Dias, R.M., Mayhew, J.L. and Cyrino, E.S. (2014) 'Reliability of one-repetition maximum test in untrained young adult men and women', *Isokinetics and Exercise Science*, 22(3), 175-182.

Ritti-Dias, R.M.R., Cyrino, E.S., Salvador, E.P., Caldeira, L.F.S., Nakamura, F.Y., Papst, R.R., Bruna, N. and Gurjão, A.L.D. (2005) 'Influence of familiarization process on muscular strength assessment in 1-RM tests', *Revista Brasileira de Medicina do Esporte*, 11(1), 39-42.

Ritti-Dias, R.M., Avelar, A., Salvador, E.P. and Cyrino, E.S. (2011) 'Influence of previous experience on resistance training on reliability of one-repetition maximum test', *Journal of Strength & Conditioning Research*, 25(5), 1418-1422.

Roberts, B.M., Nuckols, G. and Krieger, J.W. (2020) 'Sex differences in resistance training: A systematic review and meta-analysis', *Journal of Strength & Conditioning Research*, 34(5), 1448-1460.

Rodríguez-Rosell, D., Pareja-Blanco, F., Aagaard, P. and González-Badillo, J.J. (2017) 'Physiological and methodological aspects of rate of force development assessment in human skeletal muscle', *Clinical Physiology and Functional Imaging*, 38(5), 743-762.

Ryman Augustsson, S. and Svantesson, U. (2013) 'Reliability of the 1 RM bench press and squat in young women', *The European Journal of Physiotherapy*, 15(3), 118-126.

Sahaly, R., Vandewalle, H., Driss, T. and Monod, H. (2001) 'Maximal voluntary force and rate of force development in humans–importance of instruction', *European Journal of Applied Physiology*, 85(3-4), 345-350.

Sahaly, R., Vandewalle, H., Driss, T. and Monod, H. (2003) 'Surface electromyograms of agonist and antagonist muscles during force development of maximal isometric exercises—effects of instruction', *European Journal of Applied Physiology*, 89(1), 79-84.

Sale, D.G. (1988) 'Neural adaptation to resistance training', *Medicine and Science in Sports and Exercise*, 20(5 Suppl), S135-45.

Sale, D., Martin, J. and Moroz, D. (1992) 'Hypertrophy without increased isometric strength after weight training', *European Journal of Applied Physiology and Occupational Physiology*, 64(1), 51-55.

Sannicandro, I., Cofano, G., Rosa, R.A. and Piccinno, A. (2014) 'Balance training exercises decrease lower-limb strength asymmetry in young tennis players', *Journal of Sports Science & Medicine*, 13(2), 397.

Sarabon, N., Kozinc, Z., Bishop, C. and Maffiuletti, N. (2020) 'Factors influencing bilateral deficit and inter-limb asymmetry of maximal and explosive strength: motor task, outcome measure and muscle group', *European Journal of Applied Physiology*, 120, 1681–1688.

Sato, K. and Heise, G.D. (2012) 'Influence of weight distribution asymmetry on the biomechanics of a barbell back squat', *Journal of Strength & Conditioning Research*, 26(2), 342-349.

Schoenfeld, B.J., Grgic, J., Ogborn, D. and Krieger, J.W. (2017) 'Strength and hypertrophy adaptations between low-vs. high-load resistance training: a systematic review and meta-analysis', *Journal of Strength & Conditioning Research*, 31(12), 3508-3523.

Shaw, C.E., McCully, K.K. and Posner, J.D. (1995) 'Injuries during the one repetition maximum assessment in the elderly', *Journal of Cardiopulmonary Rehabilitation and Prevention*, 15(4), 283-287.

Soares-Caldeira, L.F., Ritti-Dias, R.M., Okuno, N.M., Cyrino, E.S., Gurjão, A.L.D. and Ploutz-Snyder, L.L. (2009) 'Familiarization indexes in sessions of 1-RM tests in adult women', *Journal of Strength & Conditioning Research*, 23(7), 2039-2045.

Sole, G., Hamrén, J., Milosavljevic, S., Nicholson, H. and Sullivan, S.J. (2007) ‘Test-retest reliability of isokinetic knee extension and flexion’, *Archives of Physical Medicine and Rehabilitation*, 88(5), 626-631.

Speirs, D.E., Bennett, M.A., Finn, C.V. and Turner, A.P. (2016) 'Unilateral vs. bilateral squat training for strength, sprints, and agility in academy rugby players', *Journal of Strength & Conditioning Research*, 30(2), 386-392.

Speranza, M.J., Gabbett, T.J., Johnston, R.D. and Sheppard, J.M. (2016) 'Effect of strength and power training on tackling ability in semiprofessional rugby league players', *Journal of Strength & Conditioning Research*, 30(2), 336-343.

Stone, M.H., Potteiger, J.A., Pierce, K.C., Proulx, C.M., O'Bryant, H.S., Johnson, R.L. and Stone, M.E. (2000) 'Comparison of the effects of three different weight-training programs on the one repetition maximum squat', *Journal of Strength & Conditioning Research*, 14(3), 332-337.

Styles, W.J., Matthews, M.J. and Comfort, P. (2016) 'Effects of strength training on squat and sprint performance in soccer players', *Journal of Strength & Conditioning Research*, 30(6), 1534-1539.

Suchomel, T.J., Nimphius, S. and Stone, M.H. (2016) 'The importance of muscular strength in athletic performance', *Sports Medicine*, 46(10), 1419-1449.

Swinton, P.A., Lloyd, R., Keogh, J.W., Agouris, I. and Stewart, A.D. (2012) 'A biomechanical comparison of the traditional squat, powerlifting squat, and box squat', *Journal of Strength & Conditioning Research*, 26(7), 1805-1816.

Swinton, P.A., Hemingway, B.S., Saunders, B., Gualano, B. and Dolan, E. (2018) 'A statistical framework to interpret individual response to intervention: paving the way for personalized nutrition and exercise prescription', *Frontiers in Nutrition*, 5, 41.

Taber, C., Bellon, C., Abbott, H. and Bingham, G.E. (2016) 'Roles of maximal strength and rate of force development in maximizing muscular power', *Strength & Conditioning Journal*, 38(1), 71-78.

Taylor, K., Chapman, D., Cronin, J., Newton, M.J. and Gill, N., 2012. Fatigue monitoring in high performance sport: a survey of current trends. *Journal of Australian Strength and Conditioning*, 20(1), pp.12-23.

Thorstensson, A, Grimby, G, and Karlsson, J. (1976) ‘Force-velocity relations and fiber composition in human knee extensor muscles’, *Journal of Applied Physiology*, 40(1), 12–16.

Tillin, N.A., Pain, M.T. and Folland, J.P. (2011) ‘Short-term unilateral resistance training affects the agonist–antagonist but not the force–agonist activation relationship’, *Muscle & Nerve*, 43(3), 375-384.

Tillin, N.A., Pain, M.T.G. and Folland, J. (2013) 'Explosive force production during isometric squats correlates with athletic performance in rugby union players', *Journal of Sports Sciences*, 31(1), 66-76.

van den Tillaar, R., Andersen, V. and Saeterbakken, A.H. (2014) 'The existence of a sticking region in free weight squats', *Journal of Human Kinetics*, 42(1), 63-71.

Walker, S., Davis, L., Avela, J. and Häkkinen, K. (2012) 'Neuromuscular fatigue during dynamic maximal strength and hypertrophic resistance loadings', *Journal of Electromyography and Kinesiology*, 22(3), 356-362.

Warren, G.L., Park, N.D., Maresca, R.D., McKibans, K.I. and Millard-Stafford, M.L. (2010) 'Effect of caffeine ingestion on muscular strength and endurance: a meta-analysis', *Medicine & Science in Sports & Exercise*, 42(7), 1375-1387.

Weir, J.P. (2005) 'Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM', *Journal of Strength & Conditioning Research*, 19(1), 231-240.

Wellsandt, E., Failla, M.J. and Snyder-Mackler, L. (2017) 'Limb symmetry indexes can overestimate knee function after anterior cruciate ligament injury', *Journal of Orthopaedic & Sports Physical Therapy*, 47(5), 334-338.

Wickiewicz, T.L., Roy, R.R., Powell, P.L., Perrine, J.J. and Edgerton, V.R. (1984) 'Muscle architecture and force-velocity relationships in humans', *Journal of Applied Physiology*, 57(2), 435-443.

Wilk, M., Golas, A., Zmijewski, P., Krzysztofik, M., Filip, A., Del Coso, J. and Tufano, J.J. (2020) 'The Effects of the movement tempo on the one-repetition maximum Bench Press results', *Journal of Human Kinetics*, 72(1), 151-159.

Willardson, J.M. (2006) 'A brief review: factors affecting the length of the rest interval between resistance exercise sets', *Journal of Strength and Conditioning Research*, 20(4), 978.

Wilson, G.J., Newton, R.U., Murphy, A.J. and Humphries, B.J. (1993) 'The optimal training load for the development of dynamic athletic performance', *Medicine and Science in Sports and Exercise*, 25(11), 1279-1286.

Wisløff, U., Castagna, C., Helgerud, J., Jones, R. and Hoff, J. (2004) 'Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players', *British Journal of Sports Medicine*, 38(3), 285-288.

Zourdos, M.C., Klemp, A., Dolan, C., Quiles, J.M., Schau, K.A., Jo, E., Helms, E., Esgro, B., Duncan, S. and Merino, S.G. (2015) 'Novel resistance training–specific rating of perceived exertion scale measuring repetitions in reserve', *Journal of Strength & Conditioning Research*, 30(1), 267-275.

Appendix 1

Ethical documentation

UNIVERSITY of LIMERICK

OLLSCOIL LUIMNIGH

Volunteer Information Sheet

An investigation of the sensitivity of an isometric squat test to detect resistance training induced changes in muscle function

What is the project about?

Muscle strength testing is important for sport science research as well as strength and conditioning practices by providing information about the physical capacity of an individual. This can be done using a number of different tests which include isometric multi-joint tests such as the isometric squat. This project aims to assess the sensitivity of an isometric squat test to detect resistance exercise induced changes in muscle function.

Requirements of the study

I). Familiarisation session – In order to conduct valid baseline tests you need to be familiar with the test procedures. The familiarisation session serves to acquaint you with the outcome measures of the back squat 1 repetition maximum (1RM) and the isometric squat (ISQ). Prior to this you will be required to record your dietary intake for 24 hours immediately prior to the session and instructed to repeat this at each testing session. The familiarisation session will take about 45 to 60 minutes.

II). Baseline measures – This will consist of a baseline assessment of muscle function using the 1RM and the ISQ. There will be a minimum of 48 hours between this familiarisation session and baseline strength tests. The time commitment for this day will be 45 to 60 minutes.

III). 6 week intervention – During this period you will be provided with a 2 day per week progressive weight training program that will be conducted in the PESS building under supervision by a qualified instructor. Training sessions will take approximately 60 minutes.

IV). Post-test measures – This will be a repeat of the measures that were taken at baseline.

All aspects of the study will be clearly explained to you by the researchers/instructors throughout. If you are happy to proceed you will be asked to provide written informed consent and scheduled to attend the PESS Building at the University of Limerick. If you are unsure of the location you can agree to meet one of the researchers at the Right Track Café in the PESS building (just inside the front door of the PESS Building).

You will have to report to each session in exercise clothing with ***shorts*** having performed ***no strenuous exercise 48-hours prior to testing, maintaining dietary habits prior to each study day.***

Finally, you will be required to abstain from ***any other forms of strenuous exercise*** for the duration of this study.

And that's it!

What are the benefits to you?

- You will receive 6 week of free supervised strength training and free muscle function testing.
- By partaking in this study you will be contributing to our understanding of the use of isometric multi joint tests.

What are the risks?

The procedures involved in this study have been used extensively by the researchers conducting the experiment and are generally well tolerated by subjects.

- There is minimal risk involved in the study.
- The risks involved are nothing over and above any typical exercise training protocol.
- To minimise injury risk during testing and training sessions a qualified instructors/researchers/first aider will be present at all times to monitor all sessions.

What if I do not want to take part?

- You can discontinue your participation in the research study at any time and this will be dealt with in an unhesitating and confidential manner.

What happens to the information?

- Information will be kept electronically on the principal investigator's password-protected computer, in compliance with EU GDPR. The information retrieved will be dealt with and handled in complete confidence.

Who else is taking part?

- A number of other healthy, young recreationally trained males

What if something goes wrong?

- In the unlikely event that anything untoward occurs the testing procedure will immediately cease and the PESS department emergency procedures will be followed.

What happens at the end of the study?

- At the end of the study the information will be used anonymously to present the results in thesis form, journal article and, potentially, as a communication. All subject detail/information and data will be held by the principal investigator for up to 7 years on a password-protected computer at UL in compliance with EU GDPR. Upon completion, a report containing the result of the overall study will be available to subjects on written request to the Principal Investigator.

What if I have more questions or do not understand something.

- If you do not understand any aspect of the experiment we would urge you to come forward to either of the researchers and discuss any questions that you might have. It is important that subjects feel completely at ease throughout the whole trial.

Contact Details:

Researchers:
Arthur Lynch (Principal Researcher)
E-mail: Arthur.lynch@ul.ie

Supervisor
Dr. Brian Carson (Co-Principal Investigator)
PESS Dept. University of Limerick,
Tel: +353 (0)61 234943
Email: brian.carson@ul.ie

This research study has received Ethics approval from the Education and Health Sciences Research Ethics Committee (quote approval number).
If you have any concerns about this study and wish to contact someone independent you may contact:
Chairman Education and Health Sciences Research Ethics Committee
EHS Faculty Office
University of Limerick
Tel (061) 234101
Email: ehsresearchethics@ul.ie

UNIVERSITY of LIMERICK
OLLSCOIL LUIMNIGH

Readiness Questionnaire

Name …………………………………. Age: …………………….

Date of Birth ……………………………

As you are to be a subject in this laboratory/project, please complete the following questionnaire.
Your cooperation in this is greatly appreciated.

Please tick appropriate box

	YES	NO
Has the test procedure been fully explained to you?	☐	☐

All of the following information contained herein will be treated as strictly confidential. Subjects will be given a reference number which will be used to identify them during the data analysis to ensure subjects' privacy is protected at all times.

		YES	NO
1.	Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?	☐	☐
2.	Do you feel pain in your chest when you do physical activity?	☐	☐
3.	In the past month, have you had chest pain when you were not doing physical activity?	☐	☐

4.	Do you lose your balance because of dizziness or do you ever lose consciousness?	☐	☐
5.	Do you have a muscle, bone or joint problem that could be made worse by a change in your physical activity?	☐	☐
6.	Is your doctor currently prescribing drugs for your blood pressure or heart condition?	☐	☐
7.	Do you have any known neurological disorder or symptoms of one (weakness, loss or altered sensation or pain)?	☐	☐
8.	Have you any current or previous injuries that may be affected by you taking part in this study?	☐	☐

If you have answered **NO** to questions (1-8) then you can be reasonably sure that you can take part in the requirement of the test procedure

I ………………………………………………………….. Declare that the above information is correct at the time of completing this questionnaire

Date ……… /……… /……….

Please Note: If your health changes so that you can then answer YES to any of the above questions (1-8), tell the experimenter/laboratory supervisors. Consult with your doctor regarding the level of physical activity you can conduct.

If you have answered **YES** to one or more of questions 1-8:

Talk with your doctor in person discussing with him/her those questions you answered yes. Ask your doctor if you are able to conduct the physical activity requirements.

Doctor's signature ………………………………..…… Date ……/……/…….

Signature of Experimenter………………………… Date ……/……/…….

This research study has received Ethics approval from the Education and Health Sciences Research Ethics Committee (quote approval number).
If you have any concerns about this study and wish to contact someone independent you may contact:
Chairman Education and Health Sciences Research Ethics Committee
EHS Faculty Office
University of Limerick
Tel (061) 234101
Email: ehsresearchethics@ul.ie

UNIVERSITY *of* LIMERICK
OLLSCOIL LUIMNIGH

Informed Consent

An investigation of the sensitivity of an isometric squat test to detect resistance training induced changes in muscle function

Should you agree to participate in this study please read the statements below and if you agree to them, please sign the consent form.

- I have read and understood the volunteer information sheet.
- I understand what the project is about, and what the results will be used for.
- I am fully aware that this study involves me part-taking in 2 supervised weight training sessions per week for 6 weeks.
- I understand that what the researchers find out in this study may be shared with others but that my name will not be given to anyone in any written material developed.
- I am fully aware of all of the procedures involving myself, and of any risks and benefits associated with the study.
- I know that my participation is voluntary and that I can withdraw from the project at any stage without giving any reason.
- I consent to the data obtained from the conduct of this project to be used, anonymously, for presentation and publication.

I consent (or agree) to my involvement in this research project after agreeing to all the above statements.

Name: (please print): ___________________________

Signature: ___________________________________ Date: _____________

Investigator's Signature _________________________ Date: _____________

This research study has received Ethics approval from the Education and Health Sciences Research Ethics Committee (quote approval number).
If you have any concerns about this study and wish to contact someone independent you may contact:
Chairman Education and Health Sciences Research Ethics Committee
EHS Faculty Office
University of Limerick
Tel (061) 234101
Email: ehsresearchethics@ul.ie

UNIVERSITY of LIMERICK
OLLSCOIL LUIMNIGH

Strength Training Experience

Name …………………………………. Date of Birth ……………………………

1. How long have you been weight training for? ____________________

2. How often do you undertake weight training? ____________________

3. What is your best 1RM back squat to date? ____________________

This research study has received Ethics approval from the Education and Health Sciences Research Ethics Committee (quote approval number).
If you have any concerns about this study and wish to contact someone independent you may contact:
Chairman Education and Health Sciences Research Ethics Committee
EHS Faculty Office
University of Limerick
Tel (061) 234101
Email: ehsresearchethics@ul.ie

UNIVERSITY of LIMERICK

OLLSCOIL LUIMNIGH

Previous Injury Information

Can you please provide information of any previous injuries you may have had?

Approximate date of Injury	
Duration of Injury	
Nature of Injury (eg. broken arm, hamstring strain, ACL tear)	
Have you had any reoccurring problems with this injury?	
Could this injury be potentially aggravated by participating in this study?	

This research study has received Ethics approval from the Education and Health Sciences Research Ethics Committee (quote approval number).
If you have any concerns about this study and wish to contact someone independent you may contact:
Chairman Education and Health Sciences Research Ethics Committee
EHS Faculty Office
University of Limerick
Tel (061) 234101
Email: ehsresearchethics@ul.ie

UNIVERSITY of LIMERICK

OLLSCOIL LUIMNIGH

Supplement Usage Questionnaire

(Please tick appropriate box)

1. Are you currently using any dietary supplements? This includes protein derived supplements (protein powder, amino acids, HMB etc.), stimulants (e.g. caffeine tablets, pre-workout powders etc.), vitamins, minerals, fatty acid supplements (e.g. omega-3 fish oils) or any other form of supplement?

Yes ☐ No ☐

If yes, please specify all supplements currently being used and the nature of the supplementation (frequency and dosage).

2. Have you used any form of dietary supplements within the last 6 months? This includes protein derived supplements (protein powder, amino acids, HMB etc.), stimulants (e.g. caffeine tablets, pre-workout powders etc.), vitamins, minerals, fatty acid supplements (e.g. omega-3 fish oils) or any other form of supplement?

Yes ☐ No ☐

If yes, please specify all supplements used within that timeframe and the nature of the supplementation (frequency and dosage).

This research study has received Ethics approval from the Education and Health Sciences Research Ethics Committee (quote approval number).
If you have any concerns about this study and wish to contact someone independent you may contact:
Chairman Education and Health Sciences Research Ethics Committee
EHS Faculty Office
University of Limerick
Tel (061) 234101
Email: ehsresearchethics@ul.ie

Recruitment advertisements

Interested in 6 weeks of free supervised weight training?

Researchers in the Physical Education and Sport Sciences Department at the University of Limerick are interested in assessing the effectiveness of particular weight training protocol on measures of strength in young men. The study will consist of a 6 week supervised weight training program with a strength test before and after training. In addition to the training subjects will also receive free muscle strength assessments, all free!

Are you:

1. Male?
2. Aged 18-35?
3. Competent with free-weight strength training exercises?
4. Able to commit to 6 weeks of training?

If so then you may be eligible for this study. For more information contact Arthur.Lynch@ul.ie

This research study has received Ethics approval from the Education and Health Sciences Research Ethics Committee (quote approval number).

If you have any concerns about this study and wish to contact someone independent you may contact:

Chairman Education and Health Sciences Research Ethics Committee
EHS Faculty Office
University of Limerick
Tel (061) 234101
Email: *ehsresearchethics@ul.ie*

Interested in 6 weeks of free supervised weight training?

Researchers in the PESS Department at UL are interested in assessing the effectiveness of particular weight training protocol on measures of strength in young men. The study consists of a 6 week supervised weight training program with a strength test before & after training. In addition to the training subjects will also receive free muscle strength testing!

Are you:

1. Male?
2. Aged 18-35?
3. Competent with free-weight strength training exercises?
4. Able to commit to 6 weeks of training?

If so then you may be eligible for this study.

This research study has received Ethics approval from the Education and Health Sciences Research Ethics Committee (Approval number: 2019_01_05_EHS).
If you have any concerns about this study and wish to contact someone independent you may contact:
Chairman Education and Health Sciences Research Ethics Committee
EHS Faculty Office
University of Limerick
Tel (061) 234101
Email: ehsresearchethics@ul.ie

Contact Information

Arthur Lynch
PhD Researcher

✉ **Arthur.Lynch@ul.ie**

Appendix 2

An investigation of observed learning effects in the isometric squat and one repetition maximum back squat – a pilot study

Introduction

Learning effects are inherent to tests of maximal strength performance, though some tests may be more prone to these effects than others (Nuzzo *et al*. 2019). Marked learning effects, as indicated by significant increases in group means between test sessions, can affect the precision of a test and make it difficult to differentiate improved neuromuscular performance from skill-mediated aspects of performance between test days (Buckner *et al*. 2017). Knowledge of the observed learning effects of different maximal strength performance tests can be informative for outcome-based research as it can help indicate to what extent changes over time are as a result of improved performance vs. greater skill with the test in question. Therefore the purpose of this study was to evaluate the learning effects of two tests of lower body maximal strength; the isometric squat (ISq) and the one repetition maximum back squat (1RM). Based on previous evidence of learning effects observed for the 1RM from other populations (Ritti-Dias *et al*. 2011; Ribeiro *et al*. 2014; Nuzzo *et al*. 2019) it was hypothesized that marked learning effects would be observed in the 1RM, but not in the ISq. The latter had previously demonstrated no learning effects following a four day test protocol in a similar population of strength-trained males (Drake *et al*. 2018).

Methods

Design overview

Subjects performed three maximal effort contractions in the ISq at a 120° (ISq_{120}) and a 90° (ISq_{90}) knee angle positions, with PIF taken as the highest value across all trials. This was followed by a 1RM test. These tests were performed on five consecutive days. Within-subject test session time of day was kept consistent in order to minimize diurnal variation. Subjects were instructed to keep pre-test feeding habits consistent (e.g. same breakfast prior to testing) over the course of the five testing sessions and to abstain from caffeine prior to testing. In addition, subjects were instructed to avoid any strenuous lower body exercise for the duration of the research study.

Subjects

The study design, documentation and procedures were all approved by the University of Limerick Education and Health Sciences Research Ethics Committee, in accordance with the declaration of Helsinki (ethical approval number 2019_01_05_EHS). Inclusion criteria were as follows: (i) male, (ii) 18 to 35 years of age, (iii) in good general health with no current injuries, illness or history of disease, (iv) $\geq$ 6 months free-weight based strength training experience and performance of the back squat exercise at least once per week as part of their habitual training routines. In total, 10 subjects took part in the study (mean (SD) age 21 (0.5) y, height 181 (6.2) cm, body mass 82.1 (11.8) kg).

Procedures

Following written informed consent; eligibility screening and familiarisation with all test procedures took place on a separate test session. Procedures for testing at ISq_{120}, ISq_{90} and the 1RM were identical to those outlined in Chapter 2 and repeated on each subsequent test day. ISq testing was performed first, with the first position (i.e. ISq_{120} or ISq_{90}) randomly allocated to each subject on the first test day and this order was repeated on each subsequent test day.

Statistical analysis

A one-way repeated measures analysis of variance (ANOVA) was performed for sessions 1-5 for ISq_{120}, and ISq_{90} and 1RM, respectively.

Results

Daily mean (SD) values for the ISq_{120}, ISq_{90} and 1RM are displayed in Table 24 and Figure 26 respectively. Results from the ANOVA revealed no significant between-day differences for ISq_{120} ($P = 0.346$), ISq_{90} ($P = 0.106$) or 1RM ($P = 0.141$), suggesting that no learning effects were observed. The relative percentage of subjects that attained their highest results on each test day is presented in Table 25.

	Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**
ISq$_{120}$ (N)	1758 (591)	1822 (761)	1610 (647)	1637 (706)	1675 (656)
ISq$_{90}$ (N)	1090 (243)	1071 (298)	967 (216)	1005 (294)	1004 (276)
1RM (kg)	107 (23)	106 (27)	107 (25)	110 (27)	112 (24)

Table 24 - Daily mean (SD) for isometric squat peak force (N) and one repetition maximum back squat weight lifted (kg)

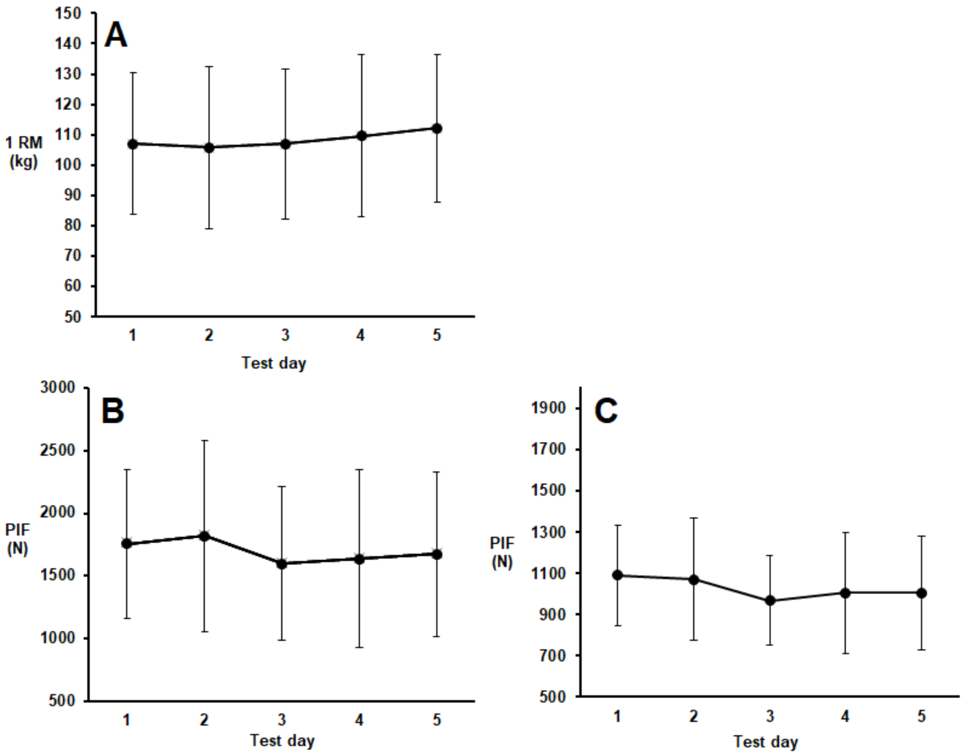

Figure 26 - Daily mean (SD) for each outcome measure. **A** represents data for the 1RM weight lifted (kg), **B** represents data for the ISq$_{120}$ (N) and **C** represents data for the ISq$_{90}$ (N). No between day differences reached significance ($P > 0.05$).

	Day 1	Day 2	Day 3	Day 4	Day 5
ISq_{120}	40%	40%	0%	10%	10%
ISq_{90}	40%	30%	0%	10%	20%
1RM	20%	10%	10%	10%	50%

Table 25 - Percentage of subjects that achieved their highest result in the ISq and 1RM across the 5 test days

Discussion

This pilot study aimed to report the reliability of two tests of lower body maximal strength; ISq_{120}, ISq_{90} and 1RM respectively using a five day consecutive testing protocol. The objective was to report any observed learning effects in these outcome measures, with the working hypothesis that the 1RM would display a marked learning effect (i.e. a significant increase in the group mean between test days), whereas the ISq would not. Overall, no significant between day differences were observed in the ISq_{120}, ISq_{90} or 1RM, indicating no learning or fatigue effects using any of these protocols (Table 24). Based on the data presented in Table 25, half of the subjects achieved their highest 1RM value on day 5, whereas the majority of subjects achieved their highest PIF value after day 2 (80 % and 70 % of the subjects in the ISq_{120} and ISq_{90} respectively). This might suggest that a learning effect was observed in the 1RM, though the magnitude of any learning effect appears to be trivial as well as being non-significant ($P > 0.05$). Practically speaking, this also suggests that the majority of moderately trained male subjects achieve their PIF in the ISq after two test sessions (Table 25). This is a useful finding as it supports the practice of conducting only 1 familiarisation session prior to a baseline testing session, as was done throughout this thesis and elsewhere (Blazevich *et al*. 2002; Bazyler *et al*. 2015; Palmer *et al*. 2017).

A number of studies have reported learning effects in the ISq and 1RM back squat. Drake *et al*. (2018) investigated the reliability of the ISq at a 90° knee angle over five test sessions. The first three sessions were considered to be familiarization sessions with the subsequent two sessions designated to be the test and re-test sessions. Significant increases in PIF were observed between familiarization sessions 1 and 3 as well as between sessions 2 and 3 ($P \leq 0.02$), which may indicate some degree of learning observed between sessions. No significant increases were observed between the designated test and re-test sessions ($P = 1.0$). Though these results suggest that at least 3 test sessions are required to establish PIF values in the ISq, this contention is not supported by the data presented in the current study. No significant between day differences in PIF were observed in either position and the majority of subjects achieved their highest PIF value by session 2 (Tables 24 and 25). This discrepancy may be related to the slighter higher training status of the subjects in Drake *et al*. (2018) as subjects had a higher 1RM squat at the time of enrolment in the study, in addition to the absence of 1RM testing, which may have generated some residual fatigue between test days in the current study. However on the basis of the data presented here, it seems appropriate to use the ISq to assess maximal strength with just one familiarisation session.

Ritti-Dias *et al*. (2005) investigated the reliability of the 1RM squat in a group of 21 male subjects with ≥ 6 months of training experience, similar to the subjects used in the current study. Four test sessions were conducted and significant increases ($P \leq 0.01$) in 1RM were observed between test day 1 and each of subsequent test days (mean (SD) 1RM day 1: 147.9 (25.1) kg, day 2: 149.6 (23.9) kg, day 3: 150.5 (24.5) kg, day 4: 151.9 (24.9) kg). This runs counter to the findings of the current study, though the differences in 1RM performance may be related to the 48-72 h interval between test sessions in Ritti-Dias *et al*. (2005). In a follow-up study, Ritti-Dias *et al*. (2011) investigated the reliability of the 1RM squat in a group of experienced (n = 16) and inexperienced (n = 14) male weight trainees. Four testing sessions were conducted, with significant increases in 1RM observed across the four test days in the non-experienced group (mean (SD) 1RM: day 1: 104.9 (25.4) kg, day 4: 116.6 (28.7) kg). Differences between days did not reach significance in the experienced group. Ribeiro *et al*. (2014) observed marked learning effects in the 1RM squat over four test days (up to an 18.5 % increase in 1RM, $P < 0.001$) in a group of 67 males of mixed training histories (0-24 months training experience). Finally, Soares-Caldeira *et al.* (2009) investigated the reliability of 1RM testing in a group of 27 women with previous weight training experience (though detrained at the time of the study). Five testing sessions were performed. 1RM weight lifted increased significantly over the five test days, though the magnitude of increase was small (mean (SD) 1RM day 1: 70.1 (14.4) kg, day 5: 73.9 (15.7) kg). Taken together, available evidence suggests the 1RM is susceptible to marked learning effects across multiple test sessions in subjects who are not highly trained. The results of the current study run somewhat at odds to the rest of the literature, with no significant changes in the group mean over the course of the 5 testing sessions ($P > 0.05$, Figure 26). Conversely, examination of the individual responses shows that 50 % of test subjects achieved their highest 1RM value on Day 5. However, the lack of significant change in the group mean suggests the 1RM is appropriate to use for the assessment of maximal strength, with a single familiarisation session (Figure 26).

Conclusion

The aim of this pilot study was to examine any potential learning effects in the ISq and the1RM back squat. Overall, no evidence of learning effects in either test were observed, which runs counter to previous evidence documenting learning effects in these measures, particularly in the 1RM (Nuzzo *et al*. 2019) and to a lesser extent the ISq (Drake *et al*. 2018). Though it may take some individuals more test sessions to establish their highest 1RM value compared to the ISq, the increases are trivial and not statistically significant. These results may be of relevance to researchers and practitioners who are considering using either the 1RM and/or the ISq as measures of lower body maximal strength. For the purpose of this thesis, the results presented here provide some justification for the use of only one familiarisation session for both ISq_{120}, ISq_{90} and the 1RM.