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Isometric strength: reliability and relationship with sprint acceleration performance

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UNIVERSITY of LIMERICK

OLLSCOIL LUIMNIGH

**Isometric Strength: Reliability and
Relationship with Sprint Acceleration
Performance**

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

Supervisors:

Dr. Thomas Comyns

Prof. Andrew Harrison

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Abstract

Isometric Strength: Reliability and Relationship with Sprint Acceleration Performance

Claire J. Brady

Introduction: In recent years, the popularity of multi-joint isometric strength testing has increased dramatically. The reliability of variables produced from the force-time curve is conflicting in the literature, and the reporting of reliability is not standardised across the research. The relationship of the isometric mid-thigh pull (IMTP) and isometric squat (ISqT) to sprint performance has been examined in field sports, including soccer and rugby, but there is a lack of research on track and field sprint athletes and hurling players. Further, there is no research examining how isometric strength relates to sprinting kinematics. **Aim:** To determine and compare the reliability of the IMTP and ISqT and investigate the relationship between isometric strength and sprint performance in track and field sprinters and field sport athletes. **Methods:** Study one involved a narrative review of the current literature to determine the level of reliability of the IMTP and ISqT and the reporting of normative data. Study two measured the reliability and usefulness of the IMTP and ISqT performed at the same knee and hip angles and determined the magnitude of differences between tests. Study three examined the relationship between the IMTP and ISqT and sprint acceleration performance among track and field sprinters. Study four explored the relationship of the IMTP and sprint kinematics among male sprinters. Study five examined the relationship between the ISqT, countermovement jump (CMJ) and reactive strength index (RSI) and sprint performance in hurling players and determined if principal component analyses (PCA) could be used to reduce the dataset to independent factors. **Results:** Study one demonstrated that peak force is the most reliable measure and can be used to determine maximum strength capabilities. Study two identified that the same measures from the force-time curve were reliable in both the IMTP and ISqT and both tests are capable of detecting changes in performance of peak force. When split by sex, female participants produced significantly greater peak force during the ISqT, with no significant differences among male participants. Among males, Study three reported large and very large correlations between IMTP and ISqT measures and 0 – 5 m time ($r = -0.517$ to -0.714 ; $p < 0.05$). Study four established higher force generation in the IMTP was associated with faster velocities at rear block clearance and step 2 ($r \geq 0.544$, $p < 0.05$) and a longer rear block clearance relative step length ($r \geq 0.547$, $p < 0.05$) in male sprinters. Study five established correlations between force at 100 ms and 0 – 5 m and 5 – 10 m ($r \geq -0.407$, $p < 0.05$), CMJ and all splits up to 30 m ($r \geq -0.391$, $p < 0.05$) and between RSI and splits over 5 m ($r \geq -0.557$, $p < 0.05$) in hurling players. The PCA identified three principal components explaining 86.1% of the variation in the dataset [SSC capabilities and sprint times (33.3%), time specific force values (29.9%) and absolute and relative strength (29.9%)]. **Conclusion:** The IMTP and ISqT are reliable tests for peak force and time dependent measures ≥ 150 ms when measured at the same knee and hip angles. Male sprinters that produce greater force are faster over the first 5 m of a sprint from the blocks and higher force generation during the IMTP is associated with faster velocities at rear block clearance and step 2 and longer rear block clearance relative step length. Among hurlers, ISqT force at 100 ms distinguished between performance levels from 0 – 5 m, players that produced higher force were faster. Isometric tests are reliable tests that correlate with early acceleration and this is important for coaches and practitioners monitoring specific types of strength that relate to initial acceleration ability.

Declaration

I hereby declare that the work contained in this thesis is my own, and was completed with counsel of my supervisors, Dr. Tom Comyns and Prof. Andrew Harrison of the Department of Physical Education and Sports Sciences, University of Limerick. This work has not been submitted to any other University or higher education institute, or for any other academic award within this University.

Claire Brady

Dr. Thomas Comyns

Prof. Andrew Harrison

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Units of Measurement

$^{\circ}$ = Degree (angle)

% = Percent

cm = Centimetre

Hz - Hertz

kg = Kilogram

m = Meter

N = Newton

N/kg = Newtons per kilogram

N/s = Newtons per second

N.s = Newton-second

s = Second

wk = Week

yr = Year

List of Abbreviations

1RM	1 repetition maximum
AG	A-gradient
AlloPF	Allometrically scaled peak force
avgRFD	Average rate of force development
CI	Confidence interval
CMJ	Countermovement jump
DJ	Drop jump
CV	Coefficient of variation
D1	Division 1
D3	Division 3
F30 ms	Starting strength
GRF	Ground reaction force
GPS	Global positioning system
ICC	Intraclass correlation coefficient
IES	Index of explosiveness
IMP	Impulse
IMTP	Isometric mid-thigh pull
ISqT	Isometric squat
JH	Jump height
mH	Meter hurdles
NCAA	National Collegiate Athletic Association
Pb	Personal best
PC	Principal components

PCA	Principal component analysis
PF	Peak force
pRFD	Peak rate of force development
RC	Reactivity coefficient
RFD	Rate of force development
RJT	Repeated jump test
RPF	Relative peak force
RSI	Reactive strength index
SD	Standard deviation
SG	S-gradient
SJ	Squat jump
SII	Sport Ireland Institute
SSC	Stretch shortening cycle
SWC	Smallest worthwhile change
S&C	Strength and Conditioning
TE	Typical error
TEM	Technical error of measurement
VIF	Variance-inflation-factor

List of Publications

Journal Publications

Chapter 2

Brady, C.J., Harrison, A.J., 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*. 1-25. Epub. DOI: 10.1080/14763141.2018.1452968. Impact Factor: 1.714. Quartile 3.

Chapter 3

Brady, C.J., Harrison, A.J., Flanagan, E.F., Haff, G.G., Comyns, T.M. 2018. A comparison of the isometric mid-thigh pull and isometric squat: intraday reliability, usefulness and the magnitude of difference between tests. *International Journal of Sports Physiology and Performance*. 13(7), 844-852. DOI: 10.1123/ijsp.2017-0480. Impact Factor: 3.979. Quartile 1.

Chapter 4

Brady, C.J., Harrison, A.J., Flanagan, E.F., Haff, G.G., Comyns, T.M. 2019. The relationship between isometric strength and sprint acceleration in sprinters. *International Journal of Sports Physiology and Performance*. (Epub ahead of print). DOI: 10.1123/ijsp.2019-0151. Impact Factor: 3.979. Quartile 1.

Chapter 5

Brady, C.J., Harrison, A.J., Flanagan, E.F., Haff, G.G., Comyns, T.M. 2019. The relationship between sprint start kinematics and the isometric mid-thigh pull in male track and field sprinters. *The Journal of Strength and Conditioning Research*. (Under review). Impact Factor: 3.017. Quartile 1.

Chapter 6

Brady, C.J., Harrison, A.J., Flanagan, E.F., Haff, G.G., Comyns, T.M. 2019. The relationship between the isometric squat and stretch shortening cycle function and sprint performance in hurling players. *Journal of Sports Science*. (Under review). Impact Factor: 2.811. Quartile 1.

Conference Presentations

Brady, C.J., Harrison, A.J., Flanagan, E.F., Comyns, T.M. The reliability of the isometric mid-thigh pull and isometric squat. Proceedings of the 35th international conference on biomechanics in sport, Cologne, Germany, 14th - 18th June 2017.

Brady, C.J., Harrison, A.J., Flanagan, E.F., Haff, G.G., Comyns, T.M. The relationship between maximum strength and acceleration performance in track and field sprint athletes. Proceedings of NSCA International Conference, Madrid, Spain. 26th – 29th September 2018.

Brady, C.J., Harrison, A.J., Flanagan, E.F., Haff, G.G., Comyns, T.M. The relationship between the isometric mid-thigh pull and sprint acceleration performance in sprinters. Proceedings of Strength and Conditioning Society 1st Annual Meeting, Rome, Italy. 18th November 2018.

Chapter 1: Introduction

1.1 Thesis Background

The research undertaken for this thesis is funded by the Irish Research Council Enterprise Partnership Scheme with Sport Ireland Institute (SII). SII aims to support athletes and coaches, to develop and deliver programmes that maximise the effectiveness of training and competition performance, by providing multidisciplinary support tailored to the needs of individual athletes or squads. The SII provides access to a range of services that can positively impact on performance. These include Nutrition, Physiology, Performance Analysis, Psychology, Biomechanics and Strength and Conditioning (S&C). S&C focuses on the physical development of athletes in order to improve elite sporting performance. The SII S&C coaches play an integral part in athletes' training regimes. The design and implementation of strength and power programmes is a central aspect of the S&C coaches' role, since strength and power are critical components of athlete performance (McGuigan *et al.* 2013). To improve the specificity and accuracy of S&C programmes, it is important to identify the athlete's strengths and weaknesses to optimise the effectiveness of the programme to enhance sports performance. The utilisation of strength and power diagnostics is a key method employed in undertaking a needs analysis, and it can have the greatest impact on the individualisation of training programmes (McGuigan *et al.* 2013).

According to McGuigan *et al.* (2013), strength and power diagnostics are used for several reasons including monitoring of acute performance in training, measuring the chronic response to training interventions and identifying the strengths and weaknesses of an athlete. There are a number of assessment techniques and methods to evaluate an athlete's strength and power levels, such as maximum strength testing, isometric tests, and plyometric jump tests. In particular, the analysis of force-time curves has been widely used to evaluate neuromuscular function (Kawamori *et al.* 2006). The amount of force generated (peak force) and the rate at which this force can be exerted (rate of force development) is important for athletic performance. Peak force (PF) and rate of force development (RFD) can be determined through an isometric force-time curve assessment protocol (Haff *et al.* 2015). Juneja *et al.* (2010) indicated that the isometric mid-thigh pull (IMTP) appears to be the most

commonly used isometric assessment when attempting to evaluate the force-time curves of athletic populations.

IMTP force-time curve assessment is performed in a custom designed isometric testing rack. A force plate is integrated into the testing system and the athlete stands on the plate while executing IMTP trials. This testing system has been widely used in research (Kawamori *et al.* 2006, Khamoui *et al.* 2011, Leary *et al.* 2012, Beckham *et al.* 2013, Haff *et al.* 2015).



Figure 1.1 - The Sorinex (Lexington, South Carolina, USA) isometric testing rack with integrated Kistler (Winterthur, Switzerland) force plate installed in the new SII training facility

In 2015, the SII was developing its new training facility and an extension to the present building was under construction, and a custom designed Sorinex (Lexington, South Carolina, USA) isometric testing rack with an integrated Kistler (Winterthur, Switzerland) force plate was being installed (Figure 1.1). This system together with an additional two force plates embedded in a lifting platform was included to allow for the implementation of sophisticated and detailed strength and power diagnostics to be undertaken on Irish Olympic athletes. The aim of the new facility was to assist the S&C coaches in assessing their athletes' strength and power profiles and plan interventions that would target their specific needs.

To advance the new testing facility, the SII and I applied for an Irish Research Council Enterprise Scheme Postgraduate Scholarship. Having been awarded the funding, the main focus was to enhance our understanding of the techniques involved in strength and power diagnostics and evaluate the correlation between athlete's strength and power profiles and sprint performance in both track and field sprinters and field sport athletes.

1.2 Background and Justification

1.2.1 Introduction to Isometric Strength Testing

Having the ability to rapidly produce high levels of force is related to several key markers of sports performance including sprinting (Baker and Nance 1999, McBride *et al.* 2009, Wang *et al.* 2016), jumping (Stone *et al.* 2003a) and change of direction ability (Spiteri *et al.* 2015, Thomas *et al.* 2015b). Since a substantial emphasis is placed upon the development and optimisation of strength and RFD during training, it is important that accurate assessment of skeletal muscle function is performed to ensure the preferred adaptations are occurring.

Assessment of an athlete's physical qualities such as maximum strength and RFD are commonly performed using dynamic and multi joint isometric testing modalities, such as the IMTP and isometric squat (ISqT). A one repetition maximum (1RM) is a common dynamic strength test, where performance in exercises such as the squat (McBride *et al.* 2009) or deadlift (Helms *et al.* 2017) are performed. RFD measures usually involve explosive movements

such as the jump squat (Baker and Nance 1999). Isometric testing, however, allows for the quantification of force, RFD and impulse (IMP) (Kawamori *et al.* 2006, Beckham *et al.* 2013, Haff *et al.* 2015). Due to the nature of isometric tests, where limited skill or mobility is required, practitioners have suggested that it is safer and more time efficient to implement isometric tests when compared to traditional measures of maximal strength and RFD such as 1RM squats or loaded jumps (Juneja *et al.* 2010). Further, it has been suggested that multiple measures of maximal force generating capacity and RFD should be performed when examining adaptations to training interventions, as a single testing modality may not be sensitive enough to determine meaningful change from baseline, potentially concealing changes in skeletal muscle function (Baker *et al.* 1994, Buckner *et al.* 2017).

The IMTP and ISqT involve pulling/pushing against an immovable bar as hard and as fast as possible (Haff *et al.* 2005). The joint positions assumed across research varies, with knee angles for the IMTP ranging from 120° to 150° (West *et al.* 2011, Comfort *et al.* 2015) and hip angle ranging from 124° to 175° (Kawamori *et al.* 2006, Beckham *et al.* 2013), possibly creating a non-optimal position. The knee angle for the ISqT ranges from 90° to 150° across research (Wilson *et al.* 1995, Blazevich *et al.* 2002).

The approaches and terminology used to assess the force-time curve of isometric testing needs to be clearly understood and consistent in its descriptions. Currently, there are a number of different approaches used and these inconsistencies leads to varying interpretation of results. For example, when analysing the force-time curve, the start point of contraction needs to be clearly identified. Comfort *et al.* (2015) defined the start point when the vertical ground reaction force (GRF) increased 40 N above the mean, West *et al.* (2011) defined the start point as the point when the first derivative exceeded the mean plus 5 standard deviations (SDs) and Haff *et al.* (2015) visually detects the start point. Some research does not clearly present the start point (Stone *et al.* 2004). When analysing time-specific force values such as Force at 100 ms and RFD (0 – 150 ms), to ensure the data is accurate and reliable, the method of calculating the onset threshold of contraction is important to consider. Further, trials analysed should have a stable pre-trial force trace with no countermovement prior to the initiation of the pull. The

absence of a stable force trace or the presence of an observable countermovement may result in the incorrect determination of force onset and therefore incorrect calculation of time-dependent force-time characteristics. Another issue that arises is the calculation of PF, where the inclusion or exclusion of body mass should be considered. The seminal paper by Haff *et al.* (1997) defined PF as PF minus the participant's body mass, whereas more recent studies include body mass in their calculation (Beckham *et al.* 2013). Some research does not clearly state their calculation methods (Stone *et al.* 2004, McGuigan *et al.* 2006). Further, there are many different methods of calculating RFD from the force-time curve and differences exist in the terminology of variables. For example, when considering the calculation method of peak RFD (pRFD) by Khamoui *et al.* (2011), they had calculated the average RFD (avgRFD) as defined by Haff *et al.* (2015) and this difference in definitions leaves the interpretation of results difficult for practitioners.

1.2.2 The Reliability of Isometric Strength Testing

It is important to ensure that the data collected to prescribe, monitor and alter an athlete's training programme is reliable. Reliability refers to the reproducibility of a measurement. High reliability increases the ability to track changes in measurements in performance testing. Poor reliability means that there is a lot of "noise" in the measurements, and results in the data being hard to interpret and provide meaningful feedback. The most common form of reliability in sport science is retest reliability, which refers to the reproducibility of values of a variable when measured under the same condition. Reliability is often measured using the intraclass correlation coefficient (ICC) and the coefficient of variation expressed as a percentage (CV%). The ICC describes the reproducibility of the rank of order of the participants on a retest, whereas the CV% describes the variation within each participant. Therefore, the two indices highlight different aspects of reliability and both should be reported to give a true indication of the reliability of a measure (Atkinson and Nevill 1998, Hopkins 2000). Further, both measures can be enhanced greatly by reporting confidence intervals (CIs) (Morrow and Jackson 1993). The majority of studies reporting reliability of the IMTP or ISqT have only reported the ICC as the reliability

measure with very few reporting the CV% and CIs. Therefore, the level of reliability of both of these tests currently reported in the literature remains unclear. While there is an extensive amount of research on the reliability of the IMTP, research on the reliability of the ISqT is far more limited, especially among the female population.

1.2.3 The Relationship of Isometric Strength to Sprint Acceleration Performance

Acceleration is an essential component of all track and field sprint events and it is a fundamental quality for field sport athletes to possess (Duthie *et al.* 2006). Sprinters and field sports athletes differ in many ways in their acceleration technique. For example, sprinters start their race from starting blocks, which requires technical ability to apply force optimally (Slawinski *et al.* 2010). Field sport athletes by comparison, accelerate from various positions such as jogging or rolling starts. There is limited research available on the sport of hurling. A recent global positioning system (GPS) study reported that during elite matches, players perform intense activity every 22 seconds, which results in 62 high speed sprints being performed per game (Collins *et al.* 2018). Therefore, the ability to accelerate over distances up to approximately 20 m is a key component for success in hurling.

The relationship between strength measured during the IMTP/ISqT and sprint performance has been examined among male soccer players and rugby players (West *et al.* 2011, Tillin *et al.* 2013, Wang *et al.* 2016). There appears to be large correlations between IMTP PF and sprint times over 5 m ($r = -0.57$) and 20 m ($r = -0.69$) amongst collegiate male soccer and Rugby League players (Thomas *et al.* 2015a). Among rugby players, large correlations have been observed between sprint time over 5 m and RFD 0 – 30 ms ($r = -0.57$) and RFD 0 – 50 ms ($r = -0.53$). Tillin *et al.* (2013) examined the relationship of ISqT force measures and sprint times among rugby players and detailed that sprint times were related to early phase ISqT force (≤ 100 ms) normalised to maximal force (i.e., expressed as a percentage of maximal force) (5 m, $r = -0.63$, $p = 0.005$ and 20 m, $r = -0.54$, $p = 0.002$). Recently, Healy *et al.* (2018) reported small relationships between IMTP PF and relative PF (RPF) and sprint performance over 40 m with 10 m splits, among national and

international level sprinters. The authors did not measure 0 – 5 m or fully diagnose the force-time curve, examining measures of strength such as RFD or IMP. The 0 – 5 m section of the race includes the “sprint start” and whilst this is rarely clearly defined, the majority of studies have usually focused on the block phase and/or one or more of the subsequent steps. In the first three steps of the 100 m race, an elite male sprinter can generate a velocity of approximately 7 m/s, which is over half of his maximum velocity (Mann and Murphy 2015). Therefore, the first 5 m is a very specific phase of the race and should be examined separately. No previous research has examined the relationship between isometric strength and sprint acceleration in hurling players.

1.2.4 Kinematic Analysis of Sprinting

Kinematic variables that describe a sprinter's performance (stride rate and stride length, contact time and flight time) have frequently been the focus of previous research (Hunter *et al.* 2004, Maćkała 2007, Lockie *et al.* 2015). Deterministic models of sprinting have been reported in the literature. For example, the deterministic model of Hay and Reid (1982) details factors that affect sprint performance, and the relationship between these factors based on simple mathematical relationships. This gives practitioners the ability to focus on key components of performance to help drive performance. Bezodis *et al.* (2019) reviewed the biomechanics of the sprint start but failed to consider the underlying strength characteristics. The majority of biomechanical research typically focuses on reporting kinematic and kinetic factors, without any additional measures of physical ability. General and specific measures of physical ability, such as force and power production have been reported to positively correlate to the push phase (exiting the blocks) (Maulder *et al.* 2006, Smirniotou *et al.* 2008) and also early acceleration (Sleivert and Taingahue 2004, Nagahara *et al.* 2014). It is unknown whether a relationship exists between physical strength, measured during a maximal isometric test and sprinting kinematics.

1.2.5 Summary

Lack of consistency in terminology and reliability measures across research may result in a lack of clarity regarding the level of reliability of the tests and the comparison of normative data. Normative data has been reported in many studies for measures of PF, RFD and IMP (Nuzzo *et al.* 2008, Beckham *et al.* 2014, Haff *et al.* 2015). This information helps to characterise a defined population at a specific point or time and creates an athlete profile, which allows the coach to determine the direction of their training (Loturco *et al.* 2016). Normative data can be useful in the interpretation of results, but the information must come from reliable data and standardised protocols. These provide a reference point for interpretation but should be used with caution. Therefore, it is essential that the protocols and analysis of the force–time curve used, the reliability measures and normative data reported are examined. Further, while the IMTP has gained popularity in the recent years, the ISqT is utilised far less by comparison. For example, on completion of a search on SPORTdiscus over the last ten years (2010 – 2019), 60 papers appear using the keyword ‘isometric mid-thigh pull’. In the ten years before this (2001 – 2010), only four papers appear using the same search strategy. Nuzzo *et al.* (2008) reported that male NCAA (National Collegiate Athletic Association) Division 1 American football players and track and field athletes produced 12.5% more RPF during the ISqT when compared with the IMTP performed at the same knee angle (140°). The majority of research studies have used males as their participants. Only one study had used female participants when testing the ISqT (Loturco *et al.* 2016). There is limited research conducted among female athletes performing an ISqT. Sex differences in strength exist in the upper body with females demonstrating weakness compared to their male counterparts (Yanovich *et al.* 2008). The main difference between an IMTP and ISqT is the elimination of the upper limb during an ISqT and being cued to “push” rather than “pull”. In addition, limited reliability research has been conducted in the ISqT on variables other than PF, such as RFD and IMP. Further, information is required on the usefulness of each test to allow practitioners make well-informed decisions on whether changes observed in scores following training interventions are both of practical significance and real. The ability to reliably detect

meaningful changes over time is a critical factor when assessing athletes. Simply identifying that an athlete performed superior in a test over time does not provide sufficient evidence that this change is actually meaningful. A meaningful change in performance can be determined by calculating the smallest worthwhile change (SWC) and comparing it to the typical error (TE) (Hopkins 2000) to allow coaches to make well informed decisions on whether a change is both of practical significance ($> \text{SWC}$) and real (greater than the noise of the test, $> \text{TE}$). No previous research has compared the reliability and results obtained during the IMTP and ISqT performed at the same knee and hip angles, identified the usefulness of each test and fully diagnosed the force-time curve of both tests.

There is a lack of research examining the relationship of isometric strength, especially derived from the ISqT and sprint performance among hurling players and track and field sprint athletes. Further, there is a need for an applied, practical test that allows for the measurement of physical abilities such as maximum force production and RFD, which relate to sprint performance. Therefore, the relationship of isometric strength to sprint performance, and how this relationship drives the performance outcomes from a kinematic perspective requires further research.

1.3 Thesis Outline

1.3.1 Aims and Objectives

The aim of this research was to determine and compare the reliability of the IMTP and ISqT and investigate the relationship between isometric strength and sprint performance in track and field sprinters and field sport athletes. The specific objectives were as follows:

- To conduct a narrative review examining the reliability of the IMTP and ISqT and the reporting of normative data (Study 1, Chapter 2).
- To determine the intraday reliability of the IMTP and ISqT performed at the same knee and hip angle, and define the usefulness of the tests and determine the magnitude of effect between the IMTP and ISqT among male and female athletes (Study 2, Chapter 3). It was hypothesised that

the IMTP and ISqT would be reliable for the same variables, PF would be able to detect changes in performance and the ISqT would produce greater measures of force in both male and female athletes.

- To investigate the relationship between the IMTP and ISqT and sprint acceleration performance in track and field sprinters (Study 3, Chapter 4). It was hypothesised that IMTP and ISqT variables would relate to 0 – 5 m sprint performance.
- To determine whether differences exist in the relationship between the IMTP and ISqT and sprint acceleration performance between males and female athletes (Study 3, Chapter 4). It was hypothesised that the relationship among the male athletes would be stronger than the relationship among the female athletes.
- To assess the relationship between the IMTP and sprint acceleration kinematics in male track and field sprinters (Study 4, Chapter 5). It was hypothesised that IMTP variables would relate to stride length and velocity in step kinematics over the first three steps.
- To explore the relationship between the ISqT, countermovement jump (CMJ), reactive strength index (RSI) and sprint performance in hurling players and also to assess if these tests could distinguish between performance levels and if principal component analyses (PCA) could be used to reduce the dataset to a collection of variables related to sprint performance (Study 5, Chapter 6). It was hypothesised that the ISqT, CMJ and RSI would relate to different phases of the 30 m sprint and that each test would distinguish between performance levels during different phases of the sprint.

1.3.2 Thesis Structure

This thesis consists of seven chapters. Five related papers were undertaken sequentially for this thesis. Chapter 2 provides a narrative review of the reliability of the IMTP and ISqT and the reporting of normative data. Chapter 3 reports the findings of the intraday reliability of the IMTP and ISqT, performed at the same knee and hip angles and details the usefulness of each

test and the magnitude of effect between both tests and male and female athletes. Chapter 4 presents the results of the relationship between the IMTP and ISqT and sprint acceleration performance in track and field sprinters. Chapter 5 presents further findings of the relationship between the IMTP and sprint acceleration kinematics in male track and field sprinters. Chapter 6 reports the findings of the relationship between the ISqT, CMJ and RSI and sprint performance in hurling players and also determined if these tests could distinguish between performance levels and if PCA could be used to reduce the dataset to a collection of variables related to sprint performance. On the day of testing, the players' also performed CMJs and the 10/5 repeated jump test (RJT) and to allow for a more in depth analysis, the results of these tests were included in the analysis. Chapter 7 provides an overview of the thesis aims and objectives, conclusions and the practical implications of the research conclusions. The limitations of the research are also considered along with future research recommendations.

Chapters 2, 3, 4, 5 and 6 are presented in journal article format with an introduction, methods, results, discussion and conclusion section. A preface section has been included in each of these chapters to give an insight regarding each study. Chapters 2, 3 and 4 have been published in peer-reviewed journals while Chapters 5 and 6 are currently under review. Minor formatting and changes to the articles have been made to aid presentation and readability of this thesis. Chapter 7 provides the thesis summary, conclusions and recommendations.

Chapter 2: Study 1 - A Review of the Reliability of Biomechanical Variables Produced during the Isometric Mid-Thigh Pull and Isometric Squat and the Reporting of Normative Data.

Brady, C.J., Harrison, A.J., 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*.

1-25

2.1 Preface

SII installed a custom designed Sorinex (Lexington, South Carolina, USA) isometric testing rack with an integrated Kistler (Winterthur, Switzerland) force plate in its new training facility. The first step in using this system was to determine the reliability of the measures taken from the force-time curve. To gain an understanding of the reliability of isometric testing, a narrative review was conducted of the current literature. The key areas to review were:

- The protocols used for isometric testing
- The level of reliability of measures from the force-time curve
- The analysis methods of the force-time curve
- The reporting of normative data

Isometric strength testing has gained popularity in recent years as indicated by the increase in published studies on its use in S&C. Given this increase in use, there is a need for a comprehensive review of the reliability of the data and a review of the reported normative data. This paper identified gaps in the literature and details practical applications for coaches and practitioners on the uses and limitations of isometric strength testing.

2.2 Abstract

The use of isometric strength testing, particularly the IMTP has increased dramatically over the last decade. The IMTP and ISqT provide one aspect of performance monitoring with variables such as PF and RFD being derived from the force-time curve. The reliability of some of these variables is conflicting in the literature, and the reporting of the reliability is not standardised across the research. The majority of research only reports ICC with very few studies reporting CVs and CIs. Additionally, methods used to calculate variables from the force-time curve differ across studies. An aim of muscle strength testing is to provide normative values for specific sports, allowing coaches to distinguish between performance levels or evaluate the effects of training on performance. This narrative review aims to evaluate studies that have researched the reliability and/or reported normative data for

both tests. Additionally, the testing protocols and the force-time curve analysis techniques utilised are discussed, concluding with practical applications for coaches on the uses and limitations of these tests. Results demonstrate that PF is the most reliable variable and can be used to determine maximum strength capabilities.

2.3 Introduction

Strength can be defined as the ability to produce force against a resistance (Stone 1993). Maximal force generating capabilities are commonly monitored in athletes and can be evaluated using dynamic or isometric muscle contractions (Haff *et al.* 2005, Beckham *et al.* 2013). According to Juneja *et al.* (2010) the IMTP appears to be the most commonly used isometric assessment when attempting to evaluate the force-time curves of athletic populations. Isometric tests such as the IMTP or ISqT may be preferred to dynamic tests such as the 1RM for their reduced injury risk, relatively simple administration and high test-retest reliability (Haff *et al.* 1997, Kawamori *et al.* 2006, Beckham *et al.* 2012, Comfort *et al.* 2015, Haff *et al.* 2015, Thomas *et al.* 2015a). Buckner *et al.* (2017) suggests that typical strength assessments such as 1RM testing are skills and that using multiple measures including isometric testing may be more advantageous for defining true measures and changes in strength. With the increased popularity of isometric tests, especially the IMTP, to assess maximum strength and an athlete's ability to exert a maximal amount of force in the shortest time possible, it is important to ensure the data being obtained to prescribe, monitor and alter an athlete's training programme is reliable. However, the majority of studies reporting reliability have only reported the ICC as the reliability measure with very few reporting the CV and 90% CIs. Although the ICC is widely accepted as a general measure of reliability, it can be greatly enhanced by reporting CIs (Morrow and Jackson 1993) and the CV (Atkinson and Nevill 1998), making a better overall interpretation of the reliability. Therefore, in many of these studies, the level of reliability reported remains unknown. In addition, the joint positions assumed for these tests differ across studies, with the knee angle for the IMTP ranging from 120 – 150° (West *et al.* 2011, Comfort *et al.*

2015) and hip angle ranging from 124 – 175° (Kawamori *et al.* 2006, Beckham *et al.* 2013) thus creating a non-optimal position, and the ISqT knee angle ranging from 90 – 150° (Wilson *et al.* 1995, Blazevich *et al.* 2002). When considering the length-tension relationship, muscles display different levels of maximum isometric force production depending on the length at which it is tested (Gordon *et al.* 1966) and therefore, it is important when testing maximal strength that the optimal length tension relationship of the muscle is used to produce the highest magnitude of force. The position assumed for the IMTP should replicate the start of the second pull phase of weightlifting movements (Haff *et al.* 1997) and for fair comparisons between the IMTP and ISqT, the joint angles should be comparable. This lack of consistency may cause some issues regarding the comparison of normative data. To accurately interpret the results of isometric strength tests, the limitations of the test must be understood. Therefore, it is essential that the protocols and analysis of the force-time curve used and the reliability measures and normative data reported are examined.

The analysis of force-time curves has been widely used to assess skeletal muscle function (Clarke 1968, Haff *et al.* 1997, Kawamori *et al.* 2006). When examining force-time curves, the quantification of the athlete's maximal force generating capacity (PF) and the slope of the force-time curve (RFD) are of particular importance and can indicate an athletes' various strength qualities (Stone *et al.* 2002). For example, PF is indicative of 'maximum strength' and RFD is indicative of the early phase of rising muscle force at the onset of contraction (Aagaard *et al.* 2002, Stone *et al.* 2002). The primary influence of these measures originates from the work of Viitasalo and Komi (1981), who determined methods of calculating the RFD, primarily during isometric leg extensions and this formed the theoretical basis for how the force-time curve generated from the IMTP is analysed. The approaches used to assess the force-time curve vary across research and this makes it hard to compare findings. Some studies do not clearly present their calculation methods, and it is unknown whether calculations include body mass (Stone *et al.* 2003b, Stone *et al.* 2004, McGuigan *et al.* 2006, Parsonage *et al.* 2016). Additionally, differences exist in calculation methods for RFD including avgRFD, pRFD and RFD reported across time epochs (e.g. 0 – 250 ms).

Research has detailed strong relationships between isometric strength tests and dynamic strength performance (Kawamori *et al.* 2006, McGuigan *et al.* 2006, McGuigan and Winchester 2008, Juneja *et al.* 2010, Bazylar *et al.* 2015). In spite of the relevance of the use of isometric assessment to monitor changes in dynamic performance, there appears to be differences in the reporting of reliability of these tests and this leaves the understanding of the relationship between isometric strength tests and dynamic strength confounding.

An important aim of strength testing is to provide normative values for particular sporting disciplines, commonly known as athletic profiling (Loturco *et al.* 2016) as well as to differentiate among different performance levels (Marinho *et al.* 2016) or to evaluate the effects of training on performance (Mangine *et al.* 2015). Normative data are also useful to help guide coaches in the interpretation of test results, but it is important to understand the limitations of these tests. For example, to compare results, the data derived must be reliable, using the same protocol and method of calculating the variables from a similar participant population and age group with a comparable training background.

This narrative review aims to evaluate and discuss the reliability of the variables derived from IMTP and ISqT testing, and collate normative values provided for various population groups. To date, no review has examined the reliability of isometric testing and the normative data derived from testing. In addition, information is provided on the background and protocols for both the IMTP and the ISqT together with a description of the biomechanical variables derived from these tests. The review concludes with practical applications for the coaches regarding the use of the IMTP and ISqT.

2.4 Methods

A narrative review approach was undertaken with 116 articles reviewed after searching PubMed, SPORTdiscus and Google Scholar using keywords ‘isometric mid-thigh pull’, ‘isometric squat’, ‘reliability’, ‘peak force’, ‘rate of force development’ and ‘force-time curve’. These keywords were used either individually and/or combined. No time criteria were applied. Inclusion

criteria were: (1) original studies of the IMTP or ISqT that reported reliability and/or normative data; (2) biomechanical variables must have been measured on a force plate; (3) participants must have been from an athletic or recreationally trained population and (4) the article must be available in English. Non-peer reviewed articles were excluded to maintain a higher strength of evidence. After exclusion of duplicate and non-eligible articles, title and abstract screening and addition of missed studies identified by reference list screening, 40 studies fulfilled the inclusion criteria. Of those, 29 studies examined the IMTP, 10 studies examined the ISqT and 1 study examined both the IMTP and ISqT. Figure 2.1 details the search strategy.

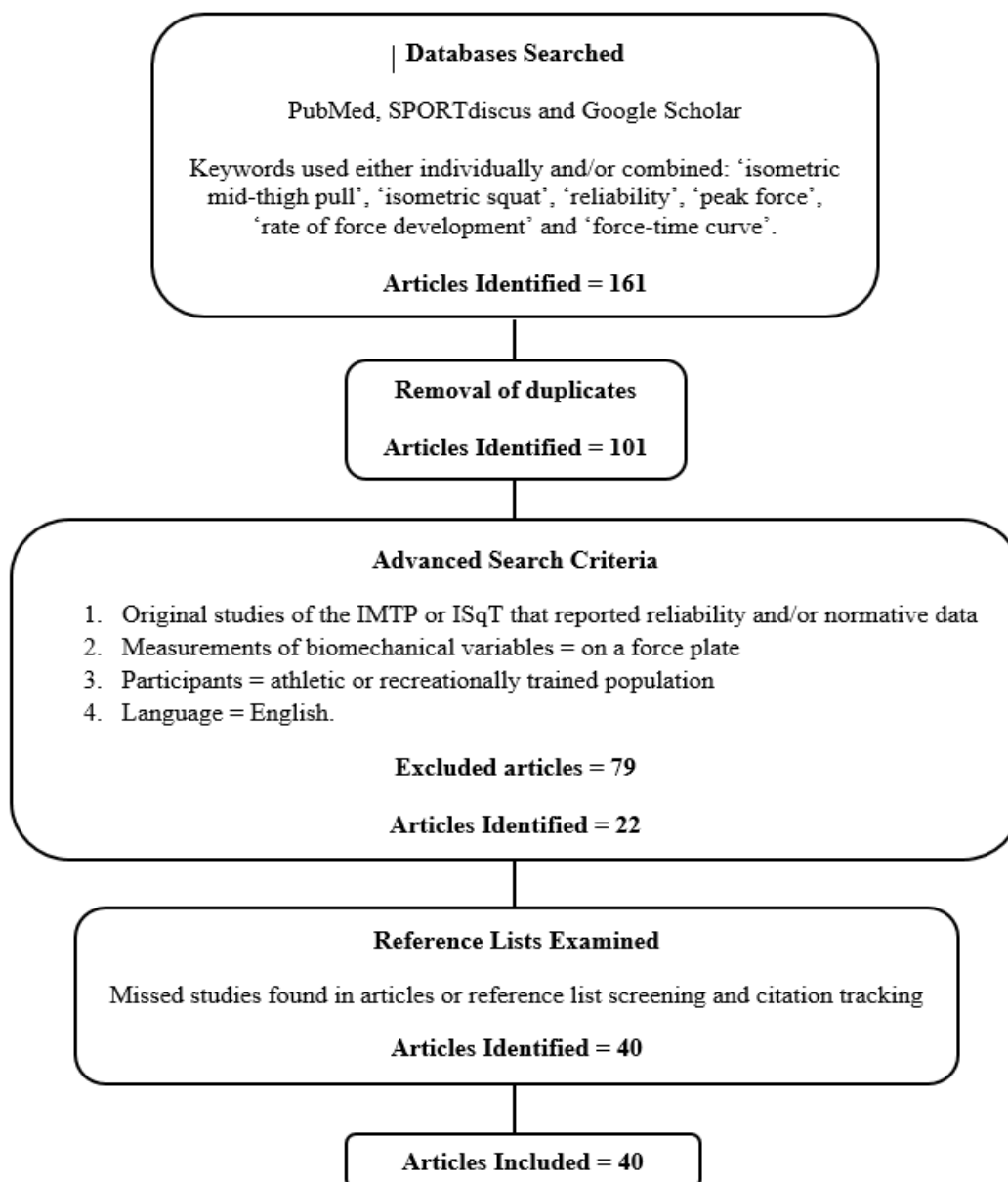


Figure 2.1 - Flow chart detailing the search strategy for the review

2.5 Results and Discussion

2.5.1 The Isometric Mid-Thigh Pull and Isometric Squat

The IMTP and ISqT are closed-chain, multi joint isometric assessments that are performed at specific joint angles to mainly measure an individual's maximum force-generating capacity and RFD. Table 2.1 outlines participant characteristics, knee and hip angles used and instructions given in previous studies for both the IMTP and Table 2.2 for the ISqT. The IMTP is designed to replicate the body position at the beginning of the second pull of the clean or snatch (Haff *et al.* 1997). The second pull position is the strongest and most powerful position during weightlifting movements and has been reported to generate the highest forces and velocities of any part of the lifts (Garhammer 1993). Haff *et al.* (2005) used 2D video analysis of lifting performance to select the most appropriate knee and hip angles for the elite weightlifters tested. To date, this is the only study, which has completed this method of matching individual anthropometric characteristics to the exact position where the highest forces are produced. This position has a knee angle of between 130 – 140° (Haff *et al.* 2008) with an upright trunk position (Haff *et al.* 1997). Knee and hip angles used in previous research vary slightly, with studies reporting knee angles of 120 – 150° (West *et al.* 2011, Comfort *et al.* 2015) and hip angles of 124 – 175° (Kawamori *et al.* 2006, Beckham *et al.* 2013). The majority of studies used a knee angle of 130 – 145° (Haff *et al.* 1997, Stone *et al.* 2003a, Haff *et al.* 2005, Kawamori *et al.* 2006, McGuigan *et al.* 2006, McGuigan and Winchester 2008, Nuzzo *et al.* 2008, Khamoui *et al.* 2011, Haff *et al.* 2015, Spiteri *et al.* 2015), which replicates the position of the second pull and is the ideal position for the participant. In relation to hip angle, Dos'Santos *et al.* (2017b) established that a hip angle of 145° produced significantly greater time-specific force values, RFD at pre-determined time bands and net forces compared to a hip angle of 175°. Additionally, Beckham *et al.* (2018) has supported a 145° hip joint angle, reporting greater IMTP kinetics compared to a flexed 125° hip joint angle. The ISqT is strongly related to performance in the 1RM barbell back squat (Blazevich *et al.* 2002, Nuzzo *et al.* 2008, Bazylar *et al.* 2015). Joint angles used in previous research range from 90 – 150° of knee flexion (Wilson *et al.* 1995, Blazevich *et al.* 2002). A knee angle of 90 – 100° was most commonly

used in previous research (Young and Bilby 1993, Blazevich *et al.* 2002, Newton *et al.* 2002, Cormie *et al.* 2007, Bazylar *et al.* 2015, Loturco *et al.* 2016) with some research using a knee angle of 140° (Nuzzo *et al.* 2008, Dumke *et al.* 2010). Very few studies have reported hip angles used during ISqT testing, however, Blazevich *et al.* (2002) reported an internal hip angle of 90° and Newton *et al.* (2002) reported a hip angle of 110°.

The IMTP and ISqT are generally performed on a custom built isometric rack, which is coupled with a force platform in order to quantify vertical GRFs. Participants are instructed to pull/push on the immovable bar as hard and fast as possible and are required to maintain the position and the effort for 5 seconds while having their force-time characteristics measured (Newton *et al.* 2002, Haff *et al.* 2005, Haff *et al.* 2015). The majority of studies use guidelines of ‘pull hard and fast’ when instructing participants during an IMTP (Haff *et al.* 2005, Kawamori *et al.* 2006, West *et al.* 2011, Beckham *et al.* 2013). Recently, Halperin *et al.* (2016) demonstrated that an externally focused instruction of ‘focus on pushing the ground as hard and as fast as you possibly can’ produced significantly greater PF compared to an internally focused and control instruction. When attempting to maximise both PF and RFD then the original instructions of ‘pull as hard and as fast’ as possible have generally been recommended.

Table 2.1 Participant characteristics, knee and hip angles and instructions given in studies using the IMTP

Study	n	Participants	Sex	Strength training background	Knee	Hip	Instruction given
					angle (°) (Mean±SD/ range)	angle (°) (Mean±SD/ range)	
Haff <i>et al.</i> (1997)	8	Trained weightlifters	M	Minimum 2 yrs	144 ± 5	145 ± 3	Pull as hard and as fast as possible
Stone <i>et al.</i> (2003b)	11	Collegiate Throwers	M & F	0.5 – 4 yrs	135 – 145	155 – 165	
Stone <i>et al.</i> (2004)	20	National Track Cyclists	M & F		140 – 145	near vertical trunk	Pull as hard and as fast as possible
Haff <i>et al.</i> (2005)	6	Elite Weightlifters	F		127 – 145		Pull as hard and as fast as possible
Kawamori <i>et al.</i> (2006)	8	Collegiate Weightlifters	M	2 yrs	141	124	Pull as hard and as fast as possible
McGuigan <i>et al.</i> (2006)	8	NCAA D3 Wrestlers	M		130		Hard and fast

Nuzzo <i>et al.</i> (2008)	12	NCAA D1 (American footballers & track and field athletes)	M & F	≥ 4 yrs	140		Pull against the bar with maximal effort as quickly as possible
McGuigan and Winchester (2008)	22	NCAA D1 American footballers	M		130		Hard and fast
Kraska <i>et al.</i> (2009)	63	Collegiate athletes	M & F		120 - 135	170- 175	Pull as hard and as fast as possible
West <i>et al.</i> (2011)	39	Elite Rugby League players	M	2 yrs	120 – 130		Pull as hard and as fast as possible
Khamoui <i>et al.</i> (2011)	19	Recreationally trained	M		127 – 145		Pull as hard and as quickly as possible
Leary <i>et al.</i> (2012)	12	Recreational golfers	M		142 \pm 5	146 \pm 11	Pull as fast and as hard as possible
Beckham <i>et al.</i> (2013)	12	Sub-elite weightlifters	M & F		125 – 135	175	Pull as fast and as hard as possible
Beckham <i>et al.</i> (2014)	106	NCAA D1 athletes	M & F		125 \pm 5		Pull as fast and as hard as you can

Haff <i>et al.</i> (2015)	12	Collegiate volleyball	F		140 ± 6.6	137.6 ± 12.9	Pull
Thomas <i>et al.</i> (2015a)	14	Collegiate soccer & Rugby League players	M		Self-selected		Pull
Darrall-Jones <i>et al.</i> (2015)	67	Junior rugby players	M		120 - 130		Pull as hard and as fast as possible
Spiteri <i>et al.</i> (2015)	12	Professional basketball players	F		140	140	Drive your feet into the force plate as hard and as fast as you can
Comfort <i>et al.</i> (2015)	24	Collegiate athletes	M	≥2 yrs	120, 130, 140 150	125, 145	Pull as hard and as fast as possible
McMahon <i>et al.</i> (2015)	15	Collegiate field sport athletes	M	≥2 yrs	Self-selected		Pull as hard and as fast as possible
Wang <i>et al.</i> (2016)	15	Collegiate Rugby Union players	M		Self-selected		Pull as hard and as fast as possible
De Witt <i>et al.</i> (2016)	9	Recreationally trained	M		144 ± 3	137 ± 3	
Dobbin <i>et al.</i> (2017)	56	Rugby League players	M	≥2 yrs	140	140	Pull as hard and as fast as possible

Dos'Santos <i>et al.</i> (2017b)	28	Collegiate athletes	M & F		145	145 and 175	Pull as hard and as fast as possible and push your feet into the force plate
Beckham <i>et al.</i> (2017)	22	Recreationally trained	M	< or > 6 months	125	125 and 145	Pull as hard and as fast as possible
Dos'Santos <i>et al.</i> (2018)	13	Youth soccer players	M	6 – 12 months	Self-selected 137 – 146	Self-selected 140 - 149	Pull as hard and as fast as possible and push your feet into the force plate

D1 = Division 1; F = female; M = male; n = number; NCAA = National Collegiate Athletic Association

Table 2.2 Participant characteristics, knee and hip angles and instructions given in studies using the ISqT

Study	n	Participants	Sex	Strength training background	Knee angle (°)	Hip angle (°)	Instruction given
Young and Bilby (1993)	18	College students	M	Inexperienced	100		Develop the force slowly and progressively until no force increase can be detected by computer
Wilson <i>et al.</i> (1995)	15	Athletes	M		110 & 150		Exert a force as hard and as fast as possible
Blazevich <i>et al.</i> (2002)	14	Competitive athletes	M	6 months	90		
Newton <i>et al.</i> (2002)	18	Healthy young and old	M	No background	90	110	Push upward against the bar with their maximal force as fast as possible
Cormie <i>et al.</i> (2007)	26	Recreationally trained	M	Strength and power training	100		
Nuzzo <i>et al.</i> (2008)	12	NCAA D1 (American	M	≥ 4 yrs strength training	140		Push with maximal effort as quickly as possible

		footballers & track and field athletes)					
Dumke <i>et al.</i> (2010)	12	Well trained distance runners	M		140		Push as quickly as possible
Hart <i>et al.</i> (2012)	11	Recreational	M	Minimum 1 yr resistance training	140	140	Push as hard and as fast as you can, until I stay stop
Tillin <i>et al.</i> (2013)	18	Collegiate Rugby Union	M	Regular strength training >3 times/wk	118	131	Push against the bar as hard as possible
Loturco <i>et al.</i> (2016)	15	Amateur boxers	M & F		90		

D1 = Division 1; F = female; M = male; n = number; NCAA = National Collegiate Athletic Association

2.5.2 Isometric Force-Time Curve Analysis

To improve practice among coaches, the approaches and terminology used to assess the force-time curve of isometric strength tests needs to be clearly understood and consistent in its descriptions. There is a great diversity in the approaches and terminology used for variables and this leads to confusion and inconsistent interpretation across studies. The force-time curves are analysed from the vertical GRF output from the force plate. An example of an IMTP force-time curve is detailed in Figure 2.2. Detail is also provided in this figure of some of the variables that can be derived from such a force-time curve. To calculate the variables that can be obtained from an IMTP/ISqT force-time curve, researchers need to identify the instant that the isometric contraction commences. This information is not always clearly presented or differs in many studies. To determine the start point, many authors use one second of quiet time (consistent vertical force) prior to the initiation of the contraction as a baseline, from which a mean and a SD are calculated (West *et al.* 2011, Comfort *et al.* 2015). Comfort *et al.* (2015) defined the start point when the vertical GRF increased 40 N above the mean and West *et al.* (2011) defined the start point as the time when the first derivative exceeded the mean plus 5 SDs. Recently, Dos'Santos *et al.* (2017a) compared five different thresholds to identify the onset of contraction during an IMTP. They concluded that coaches and scientists should use a threshold of the mean plus 5 SDs for time-specific force values for the most accurate and reliable results as this threshold eliminates the potential influence of noise. Dos Santos *et al.* (2016) sampled IMTP trials at 2000 Hz and subsequently down-sampled to 1500, 1000 and 500 Hz for analysis. High reliability was observed across all sampling frequencies for all kinetic variables, with no significant differences for each kinetic variable across sampling frequencies including time specific force values greater than 100 ms. Sampling as low as 500 Hz may be considered when measuring PF, time-specific force values and RFD at predetermined time bands, greater than 100 ms, during the IMTP for reliable data.

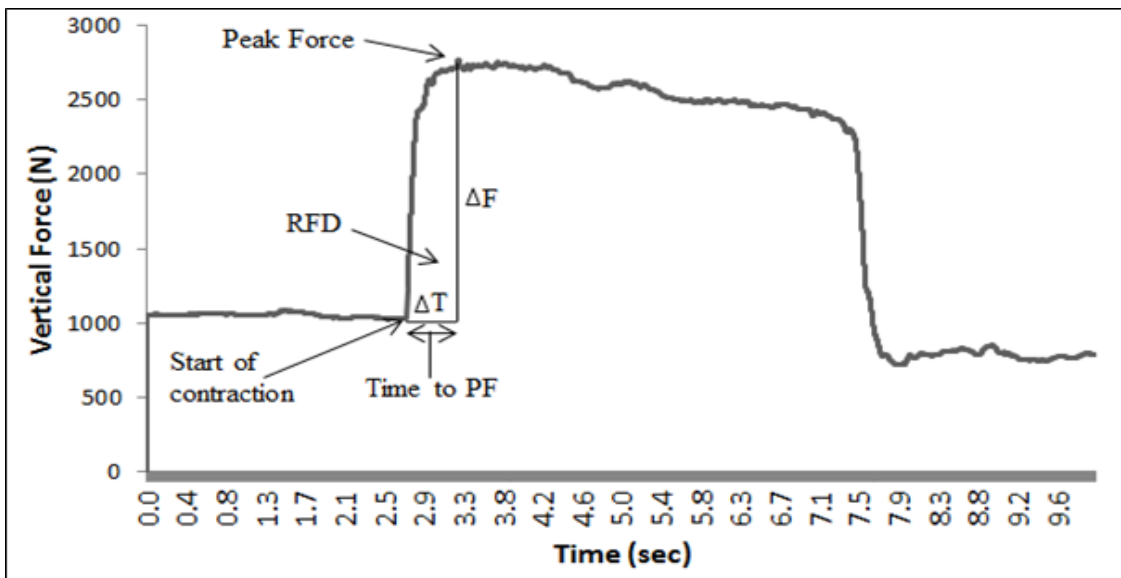


Figure 2.2 - Schematic of some of the vertical force-time measures from an IMTP

Note: PF = peak force, RFD = rate of force development, ΔF = change in force, ΔT = change in time and time to PF = time to peak force.

Variables that can be measured from the force-time curve and how these variables are calculated are summarised in Table 2.3. PF and RFD are the most common variables assessed when conducting force-time curve analysis of the IMTP (Haff *et al.* 2005). The inclusion of body mass is an important factor to consider when examining the various reported values for PF. The seminal paper by Haff *et al.* (1997), determined absolute PF as the PF produced during the IMTP minus the participant's body mass. However, more recent studies incorporate gross vertical GRF (Beckham *et al.* 2013). Notably, Dugan *et al.* (2004) carried out a review of method and calculations for determining the optimal load for jump squats. In this review, the authors note that body mass should be included in calculations for jump assessment, and it appears this is when the change occurred in including body mass in the calculation methods during isometric assessments. However, body mass is not needed in calculations for isometric assessment as there is no acceleration of body mass. Some studies do not report whether their values are gross or net forces (Stone *et al.* 2003b, Stone *et al.* 2004, McGuigan *et al.* 2006, Parsonage *et al.* 2016). Therefore, it is recommended that authors should explain in

detail their calculation methods, including whether they incorporated body mass into the calculation, as until this occurs papers are difficult to examine.

RPF is also calculated from the PF that takes into account the participant's body mass (absolute PF \div participant's body mass; N/kg). Additionally, isometric strength is often scaled allometrically (AlloPF; absolute PF \div participants body mass^{0.67}; N/kg^{0.67}) to measure muscle strength independent of body size (Jaric 2002, Jaric *et al.* 2002, Stone *et al.* 2004). Comfort and Pearson (2014) reported that when comparisons between athletes are required, ratio scaling (dividing strength by body mass) is simple and as effective as the more complex allometric scaling.

There are several methods used to calculate RFD from the isometric force-time curve. The RFD equation is applied to specific time bands such as 0 – 50, 0 – 150 and 0 – 250 ms. The RFD is then calculated by dividing the force at the end of the band by the bands time interval (Haff *et al.* 2015). The pRFD across different sampling windows is determined as the highest RFD during specific sampling windows (e.g. 10, 20, 50 ms etc.) (Haff *et al.* 1997, Haff *et al.* 2005, Kawamori *et al.* 2006, Beckham *et al.* 2012). AvgRFD is calculated by dividing the PF by the time to achieve PF (Haff *et al.* 2015). Starting strength is calculated as the force developed in the first 30 ms of contraction (F30 ms) (Young 1995). Since IMP determines change in momentum, the determination of IMP from the area under the force-time graph has important performance related characteristics. Many sport skills involve large changes in the velocity of something (e.g. shot put, javelin, long jump), and the aim is to increase the objects momentum. This is achieved by exerting a large force against the object over a long time period (by exerting a large IMP). However, in many sporting tasks there is limited time over which this force can be applied (e.g. foot contacts in maximal velocity sprinting ~ 100 ms), therefore, measurement of IMP over time periods of 0 – 50 and 0 – 250 ms can provide important performance related data.

Zatsiorsky (1995) calculated the index of explosiveness (IES), reactivity coefficient (RC), S-gradient and A-gradient to describe different portions of the force-time curve. Haff *et al.* (2015) has applied these variables to the force-time curve of an IMTP and they were reported as very unreliable,

similar to the findings of Khamoui *et al.* (2011). The IES, which is identical to the avgRFD (Haff *et al.* 2015) refers to the ability to exert maximal forces in minimal time (Harris *et al.* 2010). The RC expresses the IES relative to body weight (Harris *et al.* 2010). The S-gradient quantifies the RFD at the beginning phase of muscular effort whereas the A-gradient characterises the RFD in the late stages (Zatsiorsky 1995).

Table 2.3 Variables that can be measured from the force-time curve analysis of isometric strength tests

Variable	Abbreviation	Value	Calculation
Absolute peak force	PF	N	PF produced minus the participant's body weight
Relative peak force	RPF	N/kg	Absolute PF ÷ participants body mass (kg)
Allometric scaled peak force	AlloPF	N/kg ^{0.67}	Absolute PF ÷ participants body mass (kg) ^{0.67}
Rate of force development	RFD	N/s	$\Delta\text{Force}/\Delta\text{Time}$
Peak rate of force development	pRFD	N/s	Highest RFD during sampling windows
Average rate of force development	avgRFD	N/s	PF achieved and time between initiation of pull (0) and PF values
Impulse	IMP	N.s	avgForce x ΔTime
Index of explosiveness	IES	N/s	Same as avgRFD
Reactivity coefficient	RC		PF/(TPF x BW)
S-gradient	SG		PF _{0.5} /TPF _{0.5}
A-gradient	AG		PF _{0.5} /(TPF-TPF _{0.5})
Starting strength	F30ms	N/s	($\Delta\text{Force}/30\text{ms}$)

ΔForce = change in force; ΔTime = change in time; BW = bodyweight; N = newton; N/kg = newton's per kilogram; N/s = newton's per second; N.s = newton-second; PF_{0.5} = ½ of the absolute PF; TPF = time to PF; TPF_{0.5} = ½ of the time taken to reach PF

2.5.3 Reliability of the Isometric Mid-Thigh Pull and Isometric Squat

To determine the reliability of a test, the ICC, CV and 90% CIs (90% CI) should be calculated (Atkinson and Nevill 1998, Hopkins 2000, Haff *et al.* 2015). The ICC gives information about the degree of consistency and agreement between two sets of data. However, an ICC will not detect any systematic errors and therefore it is possible to have two sets of scores that are highly correlated but not repeatable. The CV is an estimate of measurement error and is the TE expressed as a CV (Hopkins 2015). Very few studies have reported the ICC, CV and 90% CI together (Haff *et al.* 2015, Thomas *et al.* 2015a, Thomas *et al.* 2015b), and this leaves the level of reliability questionable across the majority of studies that have only reported the ICC. While there are no predetermined standards set for biomechanical reliability, the literature has commonly used a threshold of an ICC ≥ 0.80 and a CV $\leq 10\%$ (Hopkins 2000). Haff *et al.* (2015) argues that although ICCs are commonly used to report the reliability, 90% CIs should be reported as ‘a more informative depiction of the reliability measure can be made’. The minimum acceptable reliability for the IMTP has been previously determined with an ICC > 0.7 and CV $< 15\%$ (Baumgartner and Chung 2001, Haff *et al.* 2015). An ICC close to 1 indicates ‘excellent reliability’, Vincent (1994) indicated that an ICC of 0.7 – 0.8 is questionable and > 0.9 indicates high reliability. Therefore, an ICC of > 0.7 appears to be a low level of acceptability and ideally an ICC of > 0.8 would indicate good reliability as noted by Hopkins (2000). Similarly, a CV of $< 15\%$ also appears to be too broad and preferably the analytical goal of the CV should be $\leq 10\%$ (Stokes 1985, Hopkins 2000). Table 2.4 outlines the results of reliability tests of different variables derived from an IMTP force-time curve.

The majority of previous research conducted within-session reliability. A number of more recent studies have measured both within and between session reliability (Comfort *et al.* 2015, Dos’Santos *et al.* 2017b, De Witt *et al.* 2018, Dos’Santos *et al.* 2018). Early research on the IMTP, which only reported ICCs as their reliability measure, identified PF as a highly reliable variable among weightlifters, throwers, cyclists, wrestlers, NCAA Division 1 track and field athletes and American football players, tennis, softball, soccer, volleyball, Rugby League, golfers, powerlifters (ICC ≥ 0.92) (Haff *et*

al. 1997, Stone *et al.* 2003a, Stone *et al.* 2004, Haff *et al.* 2005, Stone *et al.* 2005, Kawamori *et al.* 2006, McGuigan *et al.* 2006, McGuigan and Winchester 2008, Nuzzo *et al.* 2008, Kraska *et al.* 2009, Khamoui *et al.* 2011, West *et al.* 2011, Leary *et al.* 2012). The most common reported RFD measure in earlier research was pRFD, which was reported to be reliable across a number of studies ($ICC > 0.8$) (Stone *et al.* 2003b, Stone *et al.* 2004, Haff *et al.* 2005, Kawamori *et al.* 2006, West *et al.* 2011). When examining the pRFD, the method of calculation must be considered. Some studies use a 2 ms moving window (Haff *et al.* 1997), others use larger windows such as 20 ms (Haff *et al.* 2015) and some use the start to PF method. This must be considered when examining and comparing pRFD reliability and values. Kraska *et al.* (2009) and McGuigan *et al.* (2006) also reported RFD as reliable ($ICC \geq 0.86$). However, it is unknown how RFD was calculated in both of these studies. Khamoui *et al.* (2011) reported pRFD as unreliable ($ICC = 0.75$). However, when considering their calculation methods for pRFD, they had calculated the avgRFD as defined by Haff *et al.* (2015) and not the pRFD. When comparing the results for avgRFD of Khamoui *et al.* (2011) with those of Haff *et al.* (2015) ($ICC = 0.74$), the results are comparable. A standard set of definitions is required in order to ensure similar variables are being compared. This lack of consistency in definition of terms and calculation methods may impact the ability to benchmark results. Leary *et al.* (2012) and Beckham *et al.* (2013) reported RFD windows as reliable based on ICCs ($ICC \geq 0.81$) and Beckham *et al.* (2013) reported pRFD across a 5 ms window as reliable ($ICC = 0.97$). Additionally, Kraska *et al.* (2009) reported force at 90 ms and force at 250 ms to be reliable ($ICC \geq 0.94$); however, force at 50 ms was unreliable ($ICC = 0.79$). The level of reliability among some of these variables remains questionable having only reported ICCs. These studies failed to report the CV and CIs and this must be acknowledged when assessing whether the variables derived from these studies are reliable.

Beckham *et al.* (2012) was the first study to report the CV along with the ICC and established that PF was a reliable variable ($ICC = 0.92$ and $CV = 5\%$). The CV for PF has been reported as $\leq 4.3\%$ in several studies (Beckham *et al.* 2014, Haff *et al.* 2015, Thomas *et al.* 2015a, Thomas *et al.* 2015b). Among

junior athletes, Secomb *et al.* (2015) reported PF to be reliable in a group of competitive surfers (ICC = 0.98 and CV = 4.2%).

In relation to RFD (0 – 200 ms and maximum RFD respectively), CV > 15% have been reported even though the ICC values have been > 0.8 (Beckham *et al.* 2014, Thomas *et al.* 2015b). These CV values are outside the acceptable reliability recommendation and therefore cannot be deemed a reliable measure of RFD. Haff *et al.* (2015) measured RFD across various time band windows and these appear to meet the criteria of an ICC \geq 0.80 and a CV \leq 10% and therefore can be considered reliable variables. However, avgRFD was outside the acceptable levels of reliability (ICC = 0.74 and CV > 15%) (Haff *et al.* 2015). The authors also reported 90% CIs in conjunction with the ICC and concluded that using the predetermined RFD time bands (e.g. 0 – 50 ms, 0 – 250 ms) results in better overall reliability compared to pRFD and avgRFD measures since they resulted in a very high degree of reliability based on the lower limit of the CI falling above an ICC of 0.90 (Haff *et al.* 2015).

For RFD sampling windows, Haff *et al.* (2015) determined that only the pRFD 20 ms sampling period met both reliability criteria set by the authors, (ICC = 0.90 and CV = 12.9%), although the CV was > 10%, and based on the analytical goal of a CV \leq 10% these variable would be deemed unreliable. All other sampling periods were deemed unreliable (CV > 10%). Thomas *et al.* (2015a) and Thomas *et al.* (2015b) determined that only maximum RFD (met the ICC criteria for acceptable reliability (ICC \geq 0.93 and CV \leq 15.1%). Maximum RFD was determined by dividing the difference in consecutive vertical force readings by the time interval (0.0017 seconds) between readings. The key aspect of the Haff *et al.* (2015) was determining the reliability of the different methods used to measure RFD. When examining the reliability of RFD, the values reported must be considered in terms of the methods used as differences exist across research in the terminology used and this impacts the reliability.

Very few studies have examined the reliability of IMP measures in the IMTP. IMP at 100 ms, 200 ms and 300 ms have been reported to have a high degree of reliability (ICC \geq 0.86 and CV \leq 6.2%) with the lower limit of the CI falling above an ICC of 0.74 and upper limit of the CI falling below a CV of

9.7% (Thomas *et al.* 2015a, Thomas *et al.* 2015b). Beckham *et al.* (2014) deemed IMP at 200 ms to be reliable (ICC = 0.93 and CV = 8.4%). IMP at 100 ms, 200 ms and 300 ms was established to be reliable across different knee and hip angles (ICC = 0.87 – 0.99) by Comfort *et al.* (2015) except for within-session reliability with a knee angle of 130° and a hip angle of 125° (ICC = 0.73 – 0.74). Furthermore, Haff *et al.* (2015) detailed that the A-gradient, S-gradient and RC, were only reliable for the ICC criteria for acceptable reliability (ICC > 0.70 and CV > 15%).

Table 2.4 Results of reliability tests carried out for biomechanical variables of the IMTP

Study	n	Participants	Sex	Variable	ICC (90% CI)	CV% (90% CI)	TE
Haff <i>et al.</i> (1997)	8	Trained weightlifters	M	PF	0.93		
				pRFD	0.92		
Stone <i>et al.</i> (2003b)	11	Collegiate throwers	M & F	PF	0.98		
				pRFD	0.81		
Stone <i>et al.</i> (2004)	20	National track cyclist	M & F	PF	> 0.98		
				pRFD	> 0.80		
Haff <i>et al.</i> (2005)	6	Elite weightlifters	F	PF	0.98		
				pRFD	0.81		
Stone <i>et al.</i> (2005)	16	Elite weightlifters	M & F	PF	0.99		
Kawamori <i>et al.</i> (2006)	8	Collegiate weightlifters	M	PF	0.97		
				pRFD	0.96		

McGuigan <i>et al.</i> (2006)	8	NCAA D3 wrestlers	M	PF & RFD	≥ 0.96
Nuzzo <i>et al.</i> (2008)	12	NCAA D1 American footballers & track and field athletes	M	PF	≥ 0.98
McGuigan and Winchester (2008)	22	NCAA D1 American footballers	M	PF	0.96
Kraska <i>et al.</i> (2009)	63	Collegiate athletes; track and field athletes, tennis, softball, soccer & volleyball players	M & F	PF RFD F50 F90 F250	0.99 0.86 0.79 0.98 0.94
West <i>et al.</i> (2011)	39	Elite Rugby League players	M	PF pRFD	0.98 0.89

Khamoui <i>et al.</i> (2011)	19	Recreationally trained	M	PF & RFD windows	≥ 0.94	
				pRFD	0.75 (not acceptable)	
Leary <i>et al.</i> (2012)	12	Recreational golfers	M	PF	≥ 0.98	
				RFD windows	≥ 0.81	
Beckham <i>et al.</i> (2012)	14	Powerlifters	M	PF	0.92	5
Beckham <i>et al.</i> (2013)	12	Weightlifters	M & F	PF	0.944	
				F100	0.838	
				F150	0.887	
				F200	0.935	
				F250	0.944	
				RFD (0 – 100 ms)	0.885	
				RFD (0 – 150 ms)	0.92	
				RFD (0 – 200 ms)	0.954	
				RFD (0 – 250 ms)	0.947	
pRFD (5 ms window)	0.966					

Beckham <i>et al.</i> (2014)	106	NCAA D1 athletes	M & F	PF	0.98	4.1	
				RFD (0 – 200 ms)	0.90	16.9	
				AlloPF	0.97	4.1	
				F200	0.94	9.4	
				IMP200	0.93	8.4	
Haff <i>et al.</i> (2015)	12	Collegiate volleyball players	F	PF	0.99 (0.95-1.0)	1.7 (1.2-2.9)	
				RFD windows	>0.7	<15	
				avgRFD	0.74 (0.32-0.92)		
				pRFD20	0.74 (0.32-0.92)	>15	
				pRFD2, pRFD5, pRFD10, pRFD30, pRFD50	0.90 (0.73-0.97)	12.9 (0.5-20.7)	
				S-gradient, A-gradient, Reactivity coefficient	> 0.70	>15	
					> 0.70	>15	
Thomas <i>et al.</i> (2015a)	22	Collegiate athletes	M	PF	0.97	4.2	109.6
				RFD	0.81	15.1	2443.3

				IMP100	0.87 (0.74-0.93)	6.1 (4.9-8.3)	4.7
				IMP200	0.86 (0.74-0.93)	6.2 (5.0-8.5)	9.4
				IMP300	0.87 (0.75-0.94)	5.7 (4.6-7.8)	13.4
				TotalIMP	0.95 (0.90-0.98)	7.1 (5.7-9.7)	606.6
Thomas <i>et al.</i> (2015b)	14	Collegiate athletes; soccer and rugby players	M	PF	0.96 (0.91-0.99)	4.3 (3.3-6.5)	113.7
				RFD	0.93 (0.83-0.97)	11.1 (8.4-17)	1531.6
				IMP100	0.97 (0.91-0.99)	3.2 (2.4-4.7)	2.4
				IMP300	0.96 (0.91-0.99)	3.1 (2.4-4.7)	7.2
Comfort <i>et al.</i> (2015)	24	Collegiate athletes	M	Within session	Within session		
				PF (various hip & knee angles)	0.984 – 0.996		
				RFD	0.803 – 0.976		
				IMP100, IMP200, IMP300	0.870 – 0.990		
				IMP 130° knee & 125° hip angle	0.731 – 0.739		
				Between Session			

				PF (various hip & knee angles)	0.987 – 0.996	
				RFD		
				IMP100, IMP200, IMP300	0.803 – 0.983	
					0.819 – 0.990	
Secomb <i>et al.</i> (2015)	30	Competitive surfers	M & F	PF	0.98	4.2
McMahon <i>et al.</i> (2015)	15	Collegiate field sport athletes	M	PF	0.914	2.0
De Witt <i>et al.</i> (2016)	10	Recreationally trained		Within session		
				PF	0.97 (0.94-1.00)	
				Between session		
				PF	0.89 (0.74-1.00)	
				F250	0.80 (0.56-1.00)	
Dobbin <i>et al.</i> (2017)	56	Rugby League players	M	PF	0.912	9.2

Dos'Santos <i>et al.</i> (2017b)	28	Collegiate athletes	M & F	Within Session		
				Hip145° PF	0.99 (0.97-1.00)	2.8 (1.8-3.7)
				Hip175° PF	0.99 (0.98-1.00)	2.8 (2.1-3.5)
				Hip145° RFD (0-100 ms)	0.91 (0.82-0.96)	12.1 (8.9-15.3)
				Hip175° RFD (0-100 ms)	0.86 (0.69-0.93)	18.1 (10.7-25.5)
				Hip145° RFD (0-150 ms)	0.97 (0.93-0.98)	7.5 (4.9-10.1)
				Hip175° RFD (0-150 ms)	0.90 (0.78-0.95)	13.3 (8.4-18.1)
				Hip145° RFD (0-200 ms)	0.98 (0.95-0.99)	5.9 (3.5-8.2)
				Hip175° RFD (0-200 ms)	0.96 (0.91-0.98)	8.4 (5.9-10.8)
				Between session		
				Hip145° & PF	0.97 (0.81-0.99)	4.5 (1.6-7.3)
				Hip175° PF	0.97 (0.89-0.97)	5.3 (3.0-7.6)
				Hip145° RFD (0-100ms)	0.85 (0.36-0.96)	15.2 (9.4-21.1)
				Hip175° RFD (0-100ms)	0.68 (-0.36-0.98)	14.8 (3.0-26.5)
				Hip145° RFD (0-150ms)	0.91 (0.64-0.98)	11.9 (5.8-17.9)

				Hip175° RFD (0-150ms)	0.83 (0.73-0.98)	13.1 (4.5-21.8)	
				Hip145° RFD (0-200ms)	0.94 (0.77-0.99)	9.4 (5.6-13.1)	
				Hip175° RFD (0-200ms)	0.89 (0.59-0.97)	12.8 (5.7-19.9)	
Beckham <i>et al.</i> (2017)	22	Recreationally trained	M	Hip125° PF Experienced	0.986 (0.986-0.987)	2.7 (1.9-4.6)	
				Hip145° PF Experienced	0.997 (0.996-0.997)	1.9 (1.3-3.2)	
				Hip125° PF Inexperienced	0.964 (0.962-0.965)	5.5 (3.8-10.3)	
				Hip145° PF Inexperienced	0.984 (0.984-0.985)	2.8 (1.9-5.1)	
Dos'Santos <i>et al.</i> (2018)	13	Youth soccer players	M	Within session PF	0.98 (0.94 – 0.99)	4.1 (3.1 – 6.2)	90
				Between session PF	0.96 (0.88 – 0.99)	4.6 (3.3 – 7.7)	103

AlloPF = peak force normalised allometrically; avgRFD = average rate of force development; CV = coefficient of variation; D1 = Division 1; D3 = Division 3; F = female; F = Force; ICC = intraclass correlation coefficient; IMP= impulse; M = male; NCAA = National Collegiate Athletic Association; PF = peak force; pRFD = peak rate of force development; RFD = rate of force development; RFD windows = rate of force development windows; TE = typical error; TotalIMP = total impulse; 90%CI = 90% confidence intervals

Research on the reliability of the ISqT is limited compared to the IMTP. No study has reported the ICC together with the CV and CIs, which leaves the interpretation of results difficult for the coach. Coaches need to be cautious of this when selecting tests and associated variables. Table 2.5 summarises the results of reliability studies of the ISqT. Research has identified some reliable variables at various knee joint angles, with PF being the most reliable variable with $ICC \geq 0.97$ (Blazevich *et al.* 2002, Hart *et al.* 2012, Bazylar *et al.* 2015) and $r \geq 0.98$ (Cormie *et al.* 2007, Nuzzo *et al.* 2008). Blazevich *et al.* (2002) reported PF to be reliable among competitive athletes ($ICC = 0.97$). Cormie *et al.* (2007) and Nuzzo *et al.* (2008) also reported PF to be reliable in a group of recreationally trained and Division 1 athletes from American football and track and field ($r \geq 0.98$). By contrast, Hart *et al.* (2012) has reported the CV along with the ICC when examining the reliability of bilateral and unilateral ISqTs. PF was determined to be reliable bilaterally at a knee angle of 140° ($ICC = 0.97$ and $CV = 3.6\%$) and unilaterally at the same knee angle ($ICC = 0.98$ and $CV = 3.6\%$). However, pRFD determined as the highest RFD produced within a 30 ms window between the onset of contraction and the PF value was only reported to be reliable under one criteria of reliability in the bilateral condition ($ICC = 0.94$ and $CV = 15.2\%$) and in neither condition in unilateral condition ($ICC = 0.36$ and $CV = 45.5\%$). Bazylar *et al.* (2015) reported both PF ($ICC = 0.97 - 0.99$ and relative technical error of measurement (TEM) = 2.3 – 2.8%) and RFD (0 – 250 ms window) ($ICC = 0.9$ and relative TEM = 8.12 – 9.4%) to be reliable at both a 90° and 120° knee joint angles. IMP at 250 ms has reported to be reliable at both knee angles ($ICC = 0.95 - 0.97$ and TEM = 4.28 – 4.34%) (Bazylar *et al.* 2015).

All of the available research on the reliability of the ISqT was conducted on males. There is a lack of available research on the reliability of ISqT variables in females. There is limited reliability research on other variables such as RFD measured at different windows such as 0 – 30, 0 – 50, 0 – 90, 0 – 100, 0 – 150, 0 – 200 and 0 – 250 ms, pRFD and IMP measured across different sampling windows.

Table 2.5 Summary of participant characteristics, study design features and reliability of ISqT variables

Study	n	Participants	Sex	Knee Angle (°)	Reliability PF			Reliability RFD			Reliability IMP@250ms		
					CV	TEM	ICC/r	RFD Type	CV	TEM	ICC	TEM	ICC
Blazevich <i>et al.</i> (2002)	14	Competitive athletes	M	90			ICC = 0.97						
Cormie <i>et al.</i> (2007)	26	Recreationally trained	M	100			$r \geq 0.98$						
Nuzzo <i>et al.</i> (2008)	12	NCAA D1 (American footballers & track and field athletes)	M	140			$r \geq 0.98$						
Hart <i>et al.</i> (2012)	11	Recreationally trained	M	140 BI	3.6%		ICC = 0.97	pRFD	15.2%		0.94		
				140 UNI	3.6%		ICC = 0.98		45.5%		0.36		

Bazyler <i>et al.</i> (2015)	17	College	M	90	2.29%	ICC = 0.97 (0 - 250ms)	8.12%	0.9	4.28%	0.95
				120	2.79%	ICC = 0.99	9.44%	0.9	4.34%	0.97

BI = bilateral; CV = coefficient of variation; D1 = Division 1; ICC = intraclass correlation coefficient; IMP@250ms = impulse at 250ms; PF = Peak force; pRFD = peak rate of force development; RFD = rate of force development; TEM = technical error of measurement; UNI = Unilateral

2.5.4 Normative Values for the Isometric Mid-Thigh Pull and Isometric Squat

Studies have reported normative values for measures of PF, RFD and IMP (Stone *et al.* 2003a, Nuzzo *et al.* 2008, Beckham *et al.* 2014, Haff *et al.* 2015, Thomas *et al.* 2015a), which characterises a defined population at a specific point or period of time. Normative data helps create an athlete profile and allows the coach to determine the direction and content of their training programmes (Loturco *et al.* 2016) and evaluate the effects of training on performance (Mangine *et al.* 2015). Collecting normative data allows for the differentiation among performance levels (Marinho *et al.* 2016) and can be used in the talent identification process when combined with anthropometric and skill attributes (Hoare and Warr 2000). While normative data can be very useful in the interpretation of test results, it is important to acknowledge the limitations of using them. Firstly, the data derived must be reliable and from the same testing protocol with a clear definition of the test and methods of calculating the variables outlined to allow appropriate interpretation and generalisation of results. Secondly, the participant population group such as their age and training background needs to be similar. Finally, published normative data is generally based on group averages and the range of scores around the mean. Comparing test results to this will inform the coach how their athlete rated compared to the population average. Additionally, the results should be normalised for body weight. Normative data provides a reference point for the interpretation of the results but should be used with caution. Unless the data is reliable, obtained from athletes with a similar training background and is analysed using the same protocols and methods, coaches and practitioners should be attentive in the comparison of athletes to published normative data.

When a coach is using published normative data to assess the level of their athlete, they must first consider if the variable they are comparing against is reliable. Then they need to determine how the force-time curve was analysed to help determine if they are able to make realistic comparisons based on their analysis methods. When coaches are comparing PF, they need to determine whether the values reported include body mass. Inclusion of body mass will inflate results and this lack of consistency makes it hard to compare results as there is no consensus on the best way to analyse the results. Table 2.6

details the PF (absolute and relative) and RFD values reported in previous studies for both the IMTP and ISqT and notes whether body weight is accounted for; however, in some studies this is not clearly outlined. When comparing PF values, it is probably best to examine RPF values, instead of absolute values, to allow for the most realistic comparisons. However, not all research has reported RPF values. For example, collegiate male and female throwers and national track cyclists have reported similar absolute PF values, although it is unknown whether the values reported are gross or net values (Stone *et al.* 2003b, Stone *et al.* 2004). However, the cyclists produced more RPF compared with the throwers. Notably, the cyclists were Olympic calibre athletes and the throwers were a Division 1 college and this difference in training background may explain these results.

Beckham *et al.* (2013) reported the highest RPF values for both male and female athletes from a group of sub-elite weightlifters, calculations included the participant's body weight. It is not surprising that weightlifters are producing the highest PFs during the IMTP as the test is designed to replicate the position of the second pull of weightlifting derivatives. Therefore, these athletes are familiar with producing maximum force in this position. Powerlifters and NCAA Division 1 athletes produced similar high RPF values to the weightlifters (Beckham *et al.* 2012, Beckham *et al.* 2014). Female collegiate volleyball players have similar RPF values as male NCAA Division 1 American football players, track and field athletes, collegiate weightlifters, and road cyclists, with body weight included in the calculation (Kawamori *et al.* 2006, Nuzzo *et al.* 2008, Haff *et al.* 2015, Beattie *et al.* 2017a). The lowest reported male RPF was among Academy rugby players (under 16 years) (Darrall-Jones *et al.* 2015). In addition, Darrall-Jones *et al.* (2015) demonstrated that PF (including body weight) distinguishes between age categories in academy rugby players, with large to very large effect sizes, demonstrating that maximal isometric force can differentiate between age categories.

Nuzzo *et al.* (2008) was the only study to report RPF values and stated that male NCAA Division 1 American football players and track and field athletes produced more RPF through an ISqT compared with an IMTP with both the IMTP and ISqT performed at the same knee angle (140°). Furthermore,

Wilson *et al.* (1995) reported slightly higher ISqT absolute PF values at a knee angle of 150° compared with 110°.

The type of RFD reported differs between studies, some reported pRFD and others reporting specific time band windows or avgRFD (West *et al.* 2011, Beckham *et al.* 2014, Thomas *et al.* 2015b). Notably, the method of calculating pRFD is rarely presented in previous research. Male weightlifters pRFD values are double that of their female counterparts (Haff *et al.* 1997, Haff *et al.* 2005, Kawamori *et al.* 2006). Interestingly, Wilson *et al.* (1995) reported higher ISqT pRFD values at a knee angle of 110° compared with 150°, but the opposite was reported for PF. Notably, PF is generally more closely related to performance when compared to RFD (McGuigan *et al.* 2006, Beckham *et al.* 2013).

Thomas *et al.* (2015a) reported IMP values at 100 ms and 300 ms to be 77.1 ± 11.3 N.s and 229.7 ± 33.3 N.s respectively for male collegiate soccer and rugby players. Similar IMP values were reported by Thomas *et al.* (2015b) among male collegiate athletes from various sports.

Comparing normative data across research is challenging for many reasons. The reliability of the variables must be examined and should only be compared with variables that have reported high levels of reliability. Differences in values reported may be due to differences in sampling frequency or methods of calculating variables and this is challenging since calculation methods are not clearly presented in many studies.

Table 2.6 IMTP and ISqT peak force normative values

Test	Study	n	Participants	Sex	Body Mass (kg) (mean±SD)	Peak Force			RFD (N/s) (mean±SD)	RFD type
						Absolute (N) (mean±SD)	Relative (N/kg) (mean±SD)			
IMTP	Haff <i>et al.</i> (1997)	8	Trained weightlifters	M	95.1 ± 4.4	2847 ± 256		29693 ± 3070	Peak	
IMTP	Stone <i>et al.</i> (2003b)	11	Collegiate throwers	M & F	101.3 ± 25.3	3002 ± 933**	29.1 ± 9.1**	15000 – 18000**	Peak	
IMTP	Stone <i>et al.</i> (2004)	20	National track cyclists	M & F	77.6 ± 13.6	3591 ± 875**	46.1 ± 7.0**	12576 ± 4230**	Peak	
IMTP	Stone <i>et al.</i> (2005)	16	Elite weightlifters	M	83.4 ± 27.0	5127 ± 1056**	54.0 ± 51**			
				F	68.9 ± 18.5	3510 ± 587**	48.8 ± 9.5**			
IMTP	Haff <i>et al.</i> (2005)	6	Elite weightlifters	F	82.8 ± 18.9	3649 ± 824	43.4 ± 5.1	13997 ± 4450	Peak	
IMTP	Kawamori <i>et al.</i> (2006)	8	Collegiate weightlifters	M	85.1 ± 3.3	3178 ± 285	37.4 ± 3.4	22008 ± 4270	Peak	

IMTP	McGuigan <i>et al.</i> (2006)	8	NCAA D3 wrestlers	M	78.0 ± 4.2	2645 ± 465**	33.9 ± 5.9**	32063 ± 18834**	Peak
IMTP	Nuzzo <i>et al.</i> (2008)	12	NCAA D1 (American footballers & track and field athlete)	M	90.1 ± 14.8	3144 ± 792*	35.2 ± 6.8*	3556 ± 1026*	Peak
IMTP	McGuigan and Winchester (2008)	22	D1 American footballers	M	107.6 ± 22.9	2159 ± 218*		13489 ± 4041*	Unknown
IMTP	Kraska <i>et al.</i> (2009)	63	Collegiate athletes	M & F	72.9 ± 19.6	2138 ± 323*		12175 ± 4338*	Peak
IMTP	West <i>et al.</i> (2011)	39	Professional Rugby League	M	97.0 ± 8.2	2529 ± 398		23653 ± 7424	Peak
IMTP	Leary <i>et al.</i> (2012)	12	Recreational golfers	M	77.0 ± 9.8	2138 ± 323*			
IMTP	Beckham <i>et al.</i> (2012)	14	Powerlifters	M	109.9 ± 20.0	5829 ± 867*	53.0 ± 7.9*		
IMTP	Beckham <i>et al.</i> (2013)	12	Sub-elite weightlifters	M	96.0 ± 19.2	5942 ± 844*	63.9 ± 14.3*		
				F	66.6 ± 4.8	3743 ± 42.4*	56.4 ± 4.7*		

IMTP	Beckham <i>et al.</i> (2014)	106	NCAA D1 athletes	M & F	76.1 ± 12.7	3802 ± 1053*	50.0 ± 13.8*	6544 ± 3427	0 – 200 ms
IMTP	Haff <i>et al.</i> (2015)	12	Volleyball players	F	68.6 ± 8.2	2507 ± 421*			
IMTP	Thomas <i>et al.</i> (2015a)	22	College athletes	M	78.1 ± 10.8	2709 ± 587*	34.6 ± 5.3*	10899 ± 4543	Peak
IMTP	Thomas <i>et al.</i> (2015b)	14	Collegiate soccer & Rugby League	M	72.8 ± 9.4	2752 ± 546*			
IMTP	Secomb <i>et al.</i> (2015)	30	Competitive junior surfers	M & F	54.8 ± 12.1	1520 ± 412*			
IMTP	Darrall-Jones <i>et al.</i> (2015)	67	Academy rugby players	M – U16	79.4 ± 12.8	2158 ± 310*	28.1 ± 0.3*		
				M – U18	88.3 ± 11.9	2561 ± 339*	29.9 ± 2.9*		
				M – U21	98.3 ± 10.4	3105 ± 354*	31.4 ± 2.8*		
IMTP	McMahon <i>et al.</i> (2015)	15	Collegiate field sport athletes	M		3045 ± 497*			
IMTP	Wang <i>et al.</i> (2016)	15	Collegiate Rugby Union	M	86.5 ± 14.2	2945 ± 618			

IMTP	Parsonage <i>et al.</i> (2016)		Competitive suffers	M	72.1 ± 8.8	2422 ± 489**	33.6 ± 5.1**
				F	59.1 ± 5.4	1644 ± 252**	27.8 ± 3.3**
IMTP	Beattie <i>et al.</i> (2016)	6	Competitive road cyclist	M	69.1 ± 3.6		34.9 ± 6.0*
IMTP	Dobbin <i>et al.</i> (2017)	56	Rugby League players	M		2533 ± 243*	
						Senior players	
						1855 ± 325*	Youth players
IMTP	Dos'Santos <i>et al.</i> (2017b)	28	Collegiate athletes	M & F			
						Hip 145°	2840 ± 678*
						Hip 175°	2747 ± 627*
IMTP	Dos'Santos <i>et al.</i> (2018)	13	Youth soccer players	M		2230 ± 347*	
ISqT	Young and Bilby (1993)	18	College students	M	70.5	1902 ± 129*	
ISqT	Wilson <i>et al.</i> (1995)	15	Athletes	M - 110°	78.0 ± 8.0	1855 ± 361	14059 ± 7876 Peak

				M - 150°		1989 ± 361		11662 ± 7036	Peak
ISqT	Newton <i>et al.</i> (2002)	18	Healthy young	M	88.4 ± 12.3	1318 ± 247*			
ISqT	Cormie <i>et al.</i> (2007)	26	Recreationally trained	M	81.6 ± 18.8	2202 ± 280			
ISqT	Nuzzo <i>et al.</i> (2008)	12	NCAA D1 (American footballer & track and field athletes)	M	90.1 ± 14.8	3522 ± 635*	39.6 ± 4.6*	6102 ± 1579*	Peak
ISqT	Dumke <i>et al.</i> (2010)	12	Distance runners	M	66.7 ± 3.2	2373 ± 362*			
ISqT	Tillin <i>et al.</i> (2013)	18	Collegiate Rugby Union	M	92 ± 8	2934 ± 339			
ISqT	Loturco <i>et al.</i> (2016)	15	Amateur boxers	M	64.6 ± 12.1	2601 ± 951			
				F	(combined)	1808 ± 314			

D1 = Division 1; D3 = Division 3; F = female; M = male; n = number of participants; NCAA = National Collegiate Athletic Association; RFD = rate of force development; U16 = under 16 years of age; U18 = under 18 years of age; U21 = under 21 years of age; * = includes participants body weight; ** = unknown or unclear whether calculation includes participants body weight

2.6 Practical Implications

This review provides information that can help coaches identify the biomechanical variables that are most reliable for both the IMTP and ISqT for use in identifying their athlete's strength and weaknesses. Isometric strength tests are extremely useful since they are time efficient, especially with large groups compared with dynamic strength testing. The IMTP/ISqT may provide a truer measure of maximum strength, especially for athletes who have poor technique in traditional maximum strength tests such as restricted depth in a back squat caused by limited range ankle mobility. However, coaches should be aware of the limitations of isometric strength testing and should always perform in house reliability testing, calculating ICCs, CVs and CIs. The position assumed for the IMTP should have a knee angle of approximately 130 – 140° and an upright trunk position based on the original work by Haff *et al.* (2008). To date, it is unknown if or how many familiarisation sessions are required to attain reliable data. While many studies have reported that variables measured during the IMTP and ISqT are highly reliable, a number of these studies (n = 17) only reported the ICC. There is a lack of reliability studies using both criteria at the higher level (ICC \geq 0.80 and a CV \leq 10%) and coaches must keep this in mind when selecting the variable to report. Of the studies reported with the higher criteria, PF measured during both the IMTP and ISqT is the most reliable measure and can be used to determine an athlete's maximum strength capability. Variables such as RFD and IMP have reported to be highly reliable when measured using specific time bands; however, there are conflicting reports on the level of reliability with these variables. Normative data is useful in the interpretation of the results of isometric strength testing but there are limitations to the uses of such data sets. Caution is needed that comparisons are made across athletes of similar age, training background and gender for example. Furthermore, the analysis methods of the force-time curve must be clearly understood for realistic comparisons to be made.

Coaches should monitor isometric, dynamic and reactive strength capabilities of athletes to ensure the optimal training stimulus is provided to enhance the specific strength qualities of the athlete to help improve performance (Buckner *et al.* 2017). If this test is not highly reliable, then it will not be

appropriate to measure the different strength qualities and evaluate training programmes. If the test does not have a low CV, the degree of change would need to be much greater for a coach to be certain that a real change in athletic performance has occurred. Once a performance test is determined reliable, the SWC should be calculated and Hopkins (2000) suggests using the TE alongside the SWC to allow practitioners to make a well-informed decision on whether a change is both of practical significance ($> \text{SWC}$) and real (greater than the noise of the test, $> \text{TE}$). In addition, the difference between the IMTP and ISqT when performed at the same position is that the ISqT eliminates the use of the upper extremity. Females have been reported to be weaker in the upper extremity compared to their male counterparts (Yanovich *et al.* 2008) and more research is needed to compare biomechanical variables produced during both tests to determine which test best describes an athlete's maximum strength and ability to exert maximal force in the shortest amount of time possible.

2.7 Conclusion

The IMTP and ISqT are widely used by coaches to determine an athlete's maximum strength and ability to exert maximal force in the shortest amount of time possible. Several studies have investigated the reliability of variables such as PF, RFD and IMP. Some studies have also included variables such as A-gradient and S-gradient. It is important that the CV and CIs are reported in conjunction with the ICC so a more informative depiction of the reliability of a measure can be made. Ideally, a reliable measure should have an $\text{ICC} \geq 0.80$ and a $\text{CV} \leq 10\%$. Results confirm that PF is by far the most reliable variable and the sampling windows used in calculating the reliability of the RFD measure significantly impacts the results. Specifically, using selected time bands (e.g. 0 – 30 ms, 0 – 50 ms etc.) for the quantification of the RFD results in greater reliability when compared with the quantification of the pRFD. Research has reported high reliability for the variable of IMP during both the IMTP and ISqT and thus this variable should be measured when examining IMTP and ISqT force-time curve. Variables of pRFD, avgRFD, S-gradient, A-gradient and RC have fallen below one or both of the higher criteria for

reliability and therefore coaches should reflect on this before using these variables or normative data associated with these variables.

In spite of the reporting of the correct position used during IMTP testing, it is clear that the position varies across research and this may influence the reliability of the results. This correct position involves a knee angle between 130 – 140° with an upright trunk to mimic the position of the clean or snatch where the highest forces are produced (Garhammer 1993, Haff *et al.* 1997), and I suggest the hip angle to be 140 – 150°. While there is substantial research on the reliability of the IMTP, research on the reliability of the ISqT is far more limited. Further research is required to improve the understanding of the position used for the ISqT, and what position is the most reliable across a variety of biomechanical variables. More research is needed to determine whether the IMTP or ISqT is most reliable and most reflective of an athlete's maximal strength and ability to exert maximal force in the shortest amount of time possible.

Chapter 3: Study 2 – A Comparison of the Isometric Mid-Thigh Pull and Isometric Squat: Intraday Reliability, Usefulness, and the Magnitude of Difference Between Tests

Brady, CJ., Harrison, AJ., Flanagan, EF., Haff, GG., Comyns, TM. 2018. A comparison of the isometric mid-thigh pull and isometric squat: intraday reliability, usefulness and the magnitude of difference between tests. *International Journal of Sports Physiology and Performance*. 13(7), 844-852.

3.1 Preface

Having completed the narrative review and identified the correct protocols of isometric testing, the methods of analysing the force-time curve, the reporting of reliability and the gaps that exist in the literature, I was now in a position to carry out the reliability testing. With athletes from multiple sports using the SII on a daily basis, it was decided with the enterprise partner, to carry out this research on athletes from various sports. This allowed for a greater participant number and resulted in the best overall description of the level of reliability of the system being used on an ongoing basis. No previous research had examined the reliability of the IMTP and ISqT performed at the same knee and hip angles, detailed the magnitude of difference between each test or detailed the usefulness of each test looking at the TE compared to the SWC. This paper aimed to fill these gaps in the literature and the paper concludes with practical applications for coaches on the uses and limitations of isometric strength testing.

3.2 Abstract

Purpose: This investigation examined the reliability and usefulness of the IMTP and ISqT performed at the same knee and hip angles. The scores produced in each test were compared to determine the magnitude of differences between tests. **Methods:** Twenty-six male and female athletes (23.6 ± 4.3 y; 1.75 ± 0.07 m; 68.8 ± 9.7 kg) performed 2 maximal repetitions of the IMTP and ISqT following a specific warm up. **Results:** Maximum force, absolute PF, RPF, AlloPF, RFD (0 – 200 and 0 – 250 ms) and IMP (0 – 300 ms) were deemed reliable ($ICC \geq 0.86$ and $CV \leq 9.4\%$) in the IMTP and ISqT based on predetermined criteria ($ICC \geq 0.8$ and $CV \leq 10\%$). IMP (0 – 200 ms and 0 – 250 ms) were reliable in the ISqT ($ICC \geq 0.92$ and $CV \leq 9.9\%$). Participants produced significantly ($p < 0.05$) greater PF and IMP (0 – 300 ms) during the ISqT compared with the IMTP. When split by sex, female participants produced significantly greater PF ($p = 0.042$) during the ISqT with no significant differences among male participants ($p = 0.245$). Both tests are capable of detecting changes in performance in maximum force and absolute PF. **Conclusions:** Both tests are reliable for non-time dependent

maximal strength measures when measured at the same knee and hip angles. The ISqT may be preferred when coaches want to test an athlete's true maximum lower limb strength, especially female athletes.

3.3 Introduction

Isometric tests such as the IMTP and ISqT allow the assessment of athletes' strength qualities from a force-time curve and are used to assess skeletal muscle function (Haff *et al.* 1997, Beckham *et al.* 2013). Buckner *et al.* (2017) suggested that typical strength assessments such as 1RM testing are skills and that using multiple measures such as the IMTP or ISqT may be more advantageous for defining true measures and changes in strength. The IMTP is designed to replicate the body position at the beginning of the second pull position of the clean or the snatch (Haff *et al.* 1997). The second pull position (130 – 140° knee angle with an upright trunk position) (Haff *et al.* 1997) is the strongest and most powerful position during weightlifting movements, generating the highest forces and velocities of any part of the lifts (Garhammer 1993). From the force-time curve produced in these tests, there are a number of variables that can be examined. PF (maximum force produced) is indicative of “maximum strength” and RFD is indicative of an athlete's ability to produce maximal force in minimal time (Stone *et al.* 2002). To describe different portions of the force-time curve, Zatsiorsky (1995) calculated the IES, RC, S-gradient and A-gradient. The IES refers to the ability to exert maximal forces in minimal time and the RC expresses the IES relative to body weight (Harris *et al.* 2010). The S-gradient quantifies RFD at the beginning of muscular effort whereas the A-gradient characterises the late stages (Zatsiorsky 1995). While Haff *et al.* (2015) has applied these to the force-time curve of an IMTP, they have not yet been applied to the ISqT. IMP determines the change in momentum of an athlete and is an important performance related characteristic.

With the increased popularity of isometric tests being used to assess strength qualities, it is important that the data obtained to prescribe, monitor and alter an athlete's training programme is reliable. Superior reliability, results in better precision of single measurements and enhanced tracking of changes in

measurement in both research and practical settings (Hopkins 2000). To assess test-retest reliability, it is recommended that the ICC and the TE expressed as a CV should be calculated (Hopkins 2000) along with 95% CIs. While there are no predetermined standards set for measurements of reliability in sports science, the literature has commonly used a threshold of an $ICC \geq 0.80$ and a $CV \leq 10\%$ (Hopkins 2000).

Early research on the IMTP only reported the ICC as the reliability measure and reported PF and pRFD as reliable (Haff *et al.* 1997, Stone *et al.* 2004, Nuzzo *et al.* 2008, West *et al.* 2011). PF is by far the most reliable variable, with an $ICC \geq 0.92$ and a $CV \leq 5\%$ reported in the literature (Beckham *et al.* 2014, Haff *et al.* 2015, Thomas *et al.* 2015a, Thomas *et al.* 2015b). Research on the reliability of the ISqT is limited compared to the IMTP, but generally results in PF being the most reliable variable, with tests performed at various knee angles ($ICC \geq 0.97$) (Blazevich *et al.* 2002, Cormie *et al.* 2007, Nuzzo *et al.* 2008, Bazzyler *et al.* 2015). Variables including RFD and IMP have been reported as reliable in the IMTP (Beckham *et al.* 2014, Haff *et al.* 2015, Thomas *et al.* 2015a, Thomas *et al.* 2015b) and ISqT (Bazzyler *et al.* 2015). There are different methods for calculating the RFD including pre-set time bands, (Leary *et al.* 2012, Beckham *et al.* 2013, Haff *et al.* 2015) determining the pRFD across various windows (Haff *et al.* 1997, Haff *et al.* 2005, Leary *et al.* 2012, Beckham *et al.* 2013, Haff *et al.* 2015) and using the slope of the curve from the initial rise to the maximum force expression (avgRFD) (Khamoui *et al.* 2011, Haff *et al.* 2015). Haff *et al.* (2015) detailed that using selected time bands for the quantification of the RFD offers greater reliability compared with the quantification of the pRFDs. AvgRFD (Haff *et al.* 2015), has been deemed unreliable and pRFD during a 20 ms sampling window (pRFD20) has only met the ICC criteria for acceptable reliability ($ICC \geq 0.93$ and $CV \geq 12.9\%$) (Haff *et al.* 2015, Thomas *et al.* 2015a, Thomas *et al.* 2015b). Maffioletti *et al.* (2016) noted that smaller epochs are more sensitive to changes in the slope of the curve and therefore less reliable.

Nuzzo *et al.* (2008) reported that male NCAA Division 1 American football players and track and field athletes produced 12.5% more RPF during the ISqT when compared with the IMTP, performed at the same knee angle (140°). Both tests were reported as reliable ($r \geq 0.98$). There is limited

research conducted among female athletes performing an ISqT. Sex differences in strength exist in the upper body with females demonstrating weakness compared to their male counterparts (Yanovich *et al.* 2008). The main difference between an IMTP and ISqT is the elimination of the upper limb during an ISqT and being cued to “push” rather than “pull”. In addition, limited reliability research has been conducted in the ISqT on variables other than PF, such as RFD (sampling windows), pRFD and IMP.

Once a performance test is determined reliable, the SWC should be calculated and Hopkins (2000) suggests using the TE alongside the SWC to allow practitioners to make a well-informed decision on whether a change is both of practical significance ($> \text{SWC}$) and real (greater than the noise of the test, $> \text{TE}$). This research provides new information on the usefulness of each test examining the TE compared to the SWC.

No previous research has compared the reliability and results obtained during the IMTP and ISqT performed at the same knee and hip angles. Therefore, the aim of the current study was to determine the intraday reliability of the IMTP and ISqT performed at the same knee and hip angle, define the usefulness of the tests and determine the magnitude of effect between the IMTP and ISqT among male and female athletes. It was hypothesised that the IMTP and ISqT would be reliable for the same variables, PF would be able to detect changes in performance and that the ISqT would produce greater measures of force in both male and female athletes.

3.4 Methods

3.4.1 Participants

Sixteen male (23.0 ± 4.8 y; 1.79 ± 0.05 m; 72.8 ± 10.4 kg) and ten female athletes (24.5 ± 3.1 y; 1.68 ± 0.03 m; 62.5 ± 3.4 kg) from track and field, boxing, modern pentathlon, canoeing, rowing, badminton and Taekwondo took part in this study. All participants had at least 6 months of resistance training experience. All participants provided written informed consent prior to participation in accordance with the ethical requirements of the Research Ethics Committee.

3.4.2 Study Design

A cross-sectional study design with repeated measures was used. This study assessed the intraday reliability of the IMTP and ISqT performed at the same knee and hip angle to determine the reliability of maximum force, PF, RFD (sampling windows), pRFD, avgRFD, IMP, IES, RC, S-gradient and A-gradient. The mean scores achieved in each test were compared. All participants took part in a familiarisation session one week prior to the testing session. The IMTP/ISqTs were randomised among participants.

3.4.3 Methodology

Participants took part in a familiarisation session one week prior to the testing session that firstly included an explanation of the study and signing of the informed consent. Participants then performed a general warm up consisting of 3 minutes of cycling, 10 bodyweight squats, 10 bodyweight walking lunges and 10 gluteal bridges. Participants were then set in the correct position for the IMTP, which consisted of a mean knee angle of $136 \pm 3^\circ$ and a hip angle of $137 \pm 2^\circ$. Participants were required to maintain the position throughout the test. Knee angles and hip angles were measured using a hand-held goniometer, grip- and foot- width were measured and remained consistent between trials. Then each participant performed an IMTP specific warm up previously reported in the literature (Beattie *et al.* 2017a), which consisted of pulling the IMTP bar for 5 seconds at a self-directed 50%, 3 seconds at 70 – 80%, 3 seconds at 90% of maximal effort with 1 minute recovery between warm up efforts. Participants completed 3 maximal efforts lasting 5 seconds. During the IMTP, participants used lifting straps to standardise grip strength (Beattie *et al.* 2017a). For each trial participants were instructed to “pull as hard and as fast as you can, push the ground away, drive your feet into the ground and the bar from the floor” to ensure maximal force was achieved (Halperin *et al.* 2016). Participants were then set in the position for the ISqT, which adopted the same knee and hip angles attained during the IMTP, with the bar positioned across the shoulders. The same specific warm up and instruction was given with the exception of “push” instead of “pull”.

One week later, participants completed the testing session. The order of sequences of tests were randomised among participants. Participants completed the general warm up followed by the specific warm up of the first test to be completed. Participants were then given 2 minutes' rest before completing 2 maximal effort trials with 2 minutes between trials. Participants were instructed to get ready, to pre-tense, and then were given a countdown of "3, 2, 1, PULL!" Verbal encouragement was provided during each trial. They then rested for 5 minutes before completing the warm up for the second test (IMTP/ISqT) followed by 2 maximum efforts with 2 minutes' rest between trials. Participants completed a third trial if they lost their position or grip. If there was a difference in recorded PF of greater than 250 N between trials (Kraska *et al.* 2009) or a countermovement was visually obvious during real-time observation of the stable force trace established immediately prior to trial initiation, that trial was excluded and an additional trial was performed (Comfort *et al.* 2019).

All isometric testing was conducted on a custom-made Sorinex isometric rack (Lexington, South Carolina, USA), allowing the placement of the bar at 0.5 cm intervals permitting the desired position in each participant. The rack was anchored to the floor and placed over a Kistler (Winterthur, Switzerland) force platform sampling at 1000 Hz.

3.4.4 Isometric Force-Time Curve Analysis

All force-time curves were analysed with the use of a custom built spreadsheet to determine specific force-time characteristics. The collection period for each trial was set at 12 seconds and a baseline was measured during the 3 second countdown prior to the initiation of the pull. The criterion onset threshold and onset of the contraction was defined as the point where the force exceeded 5 SD from baseline (Dos'Santos *et al.* 2017a). The maximum force generated during the 5 seconds was reported as the maximum force. Absolute PF was reported as the maximum force minus the participant's body weight. Absolute PF was also reported relative to body mass (N/kg) and body weight (N/N). Additionally, AlloPF ($\text{N/kg}^{0.67}$) was used to measure muscle strength independent of body size (Stone *et al.* 2004).

RFD was analysed with methods previously reported in the literature (Haff *et al.* 2015). Precisely, RFD was calculated ($\Delta\text{Force}/\Delta\text{Time}$) and was applied to specific time bands (0 – 30, 0 – 50, 0 – 90, 0 – 100, 0 – 150, 0 – 200, 0 – 250 ms). pRFD was then determined as the highest RFD during a 2- (pRFD 2), 5- (pRFD 5), 10- (pRFD 10), 20- (pRFD 20), 30- (pRFD 30) and 50-millisecond (pRFD 50) sampling windows. AvgRFD was calculated from the PF achieved and the time elapsed between the initiation of the pull and the PF values. IMP was measured by average force divided by the change in time over 100 ms, 200 ms, 250 ms and 300 ms.

The IES is calculated identical to the avgRFD. The RC was calculated using the PF and time to PF and the participants body weight [$\text{PF}/(\text{TPF} \times \text{BW})$]. The S-gradient was calculated using half the PF ($\text{PF}_{0.5}$) and the time to achieve it ($\text{TPF}_{0.5}$): ($\text{PF}_{0.5}/\text{TPF}_{0.5}$). Finally the A-gradient was calculated by using the $\text{PF}_{0.5}$, TPF and $\text{TPF}_{0.5}$: [$\text{PF}_{0.5}/(\text{TPF}-\text{TPF}_{0.5})$] (Zatsiorsky 1995).

3.4.5 Statistical Analysis

All force-time data were analysed with the use of a custom spreadsheet. Normality of data was assessed by Shapiro-Wilk statistic. Reliability was calculated by determining the CV (calculated as the TE and expressed a CV%) and the ICC and 95% CIs using a Microsoft Excel spreadsheet (Hopkins 2015). Based on the 95% CI of the ICC estimate, values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.90 are indicative of poor, moderate, good, and excellent reliability, respectively (Koo and Li 2016). Acceptable reliability was determined at an $\text{ICC} \geq 0.8$ and a $\text{CV} \leq 10\%$ (Hopkins 2000). Paired *t*-tests with an alpha level of $p \leq 0.05$ were used to determine if differences existed between mean absolute PF, RPF (N/kg), AlloPF, RFD (0 – 200 ms), RFD (0 – 250 ms) and IMP (0 – 300 ms) values produced in the IMTP and ISqT. Participants were then split by sex for this analysis to determine if sex differences existed. Paired *t*-test values were reported with a Holm's sequential Bonferroni method (Holm 1979) in order to control for type I errors. To determine the magnitude of effect within group differences in test scores, a Hedges' *g* effect size test was performed between the mean values produced in the IMTP and ISqT. The magnitude of Hedges'

g was interpreted using Cohen's scale as trivial ($g < 0.2$), small ($0.2 \leq g < 0.5$), moderate ($0.5 \leq g < 0.8$) and large ($g \geq 0.8$) (Cohen 1988). TE was calculated and the usefulness of the test was determined by comparing the TE to the SWC calculated on a Microsoft Excel spreadsheet (Hopkins 2015). The SWC was determined by multiplying the between-subject SD by 0.2 ($SWC_{0.2}$) (Hopkins 2004), which is the typical small effect or 0.5 ($SWC_{0.5}$) (Cohen 1988), which is an alternate moderate effect. If the TE was below the SWC, the test was rated as "good", if the TE was similar to SWC it was rated as "ok" and if the TE was higher than the SWC the test was rated as "marginal" (Hopkins 2004).

3.5 Results

Descriptive statistics for male and female participants for the variables that attained a criterion of an $ICC \geq 0.8$ and a $CV \leq 10\%$ are detailed in Table 3.1 for the IMTP and Table 3.2 for the ISqT along with the TE, $SWC_{0.2}$ and $SWC_{0.5}$. Figure 3.1 details the variables that achieved a criterion of an $ICC \geq 0.8$ and a $CV \leq 10\%$ in either test with all variables having 'good' or 'excellent' reliability based on the lower bound 95% confidence interval (Koo and Li 2016). While IMP 0 – 200 ms and 0 – 250 ms were determined reliable in the ISqT, they were deemed unreliable in the IMTP ($CV > 10\%$). RFD (0 – 30 ms, 0 – 50 ms, 0 – 90 ms, 0 – 100 ms and 0 – 150 ms), pRFD (2 ms, 5ms, 10 ms, 20 ms, 30 ms and 50 ms), avgRFD, IMP (0 – 100 ms), IES, RC, S-gradient and A-gradient were deemed unreliable in both the IMTP and ISqT ($ICC < 0.8$ and/or $CV > 10\%$) (Figure 3.2).

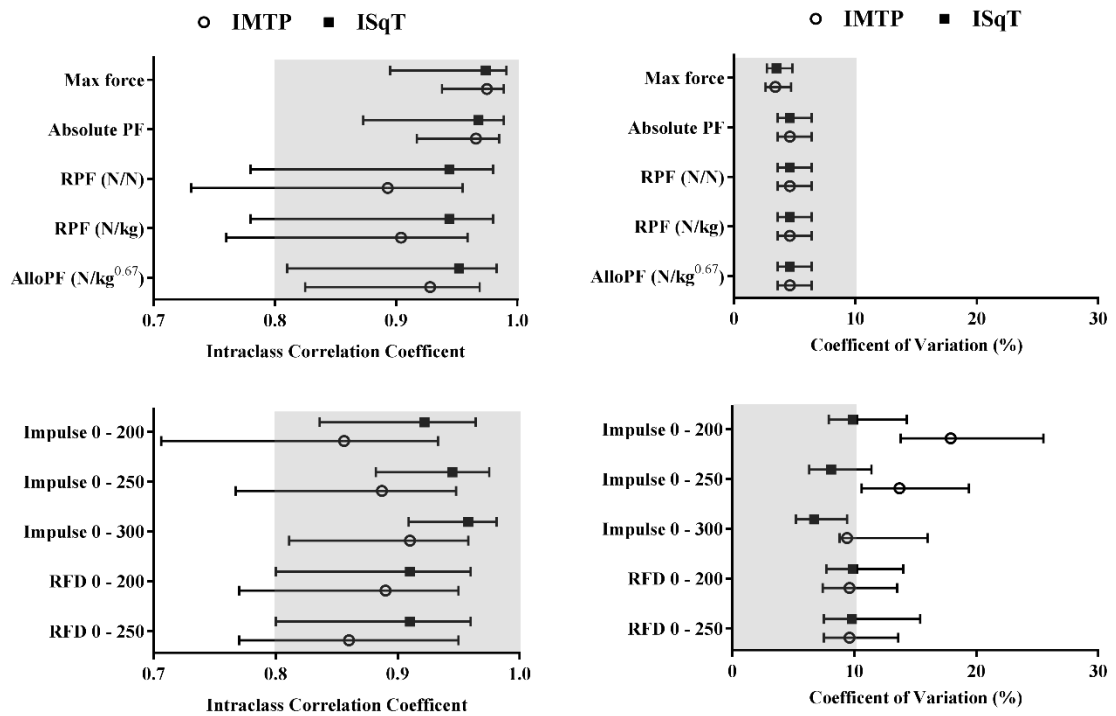


Figure 3.1 - Reliability measures of the ICC of the variables attaining an ICC ≥ 0.8 in either the IMTP or ISqT and CV% of each variable.

Note: \circ/\blacksquare = ICC/CV; error bars indicate 95% confidence limits. Grey shaded area = zone of acceptable reliability (ICC ≥ 0.8 , CV $\leq 10\%$). Max force = maximum force; PF = absolute peak force; RPF (N/N) = PF relative to body weight, N/N; RFP (N/kg) = PF relative to body mass; AlloPF = allometrically scaled PF. RFD = rate of force development; IMP = impulse; RFD 0 – 200 = RFD 0 – 200 ms sampling window; RFD 0 – 250 = RFD 0 – 250 ms sampling window. Impulse 0 – 200 = IMP 0 – 200 ms sampling window; impulse 0 – 250 = IMP 0 – 250 ms sampling window; impulse 0 – 300 = IMP 0 – 300 ms sampling window

Table 3. 1 Descriptive statistics for male and female participants for the IMTP and within session reliability variables attaining a criteria of an ICC ≥ 0.8 and a CV $\leq 10\%$

Variables	Mean \pm SD	ICC	95% CI		CV%	95% CI		TE	SWC (0.2)	Rating	SWC (0.5)	Rating
			Lower	Upper		Lower	Upper					
Maximum force (N)	2669 \pm 599	0.98	0.96	0.99	3.4	2.6	4.7	89	120	good	301	good
PF (N)	1994 \pm 513	0.97	0.94	0.99	4.6	3.6	6.4	89	103	good	259	good
RPF (N/N)	2.9 \pm 0.4	0.93	0.84	0.97	4.6	3.6	6.4	0.1	0.1	ok	0.2	good
RPF (N/kg)	28.7 \pm 4.4	0.93	0.84	0.97	4.6	3.6	6.4	1.3	0.9	good	2.2	good
AlloPF (N/kg ^{0.67})	116 \pm 20.9	0.95	0.88	0.98	4.6	3.6	6.4	5.1	4.2	marginal	10.6	good
RFD 0 – 200 ms (N/s)	5623 \pm 1447	0.89	0.77	0.95	9.6	7.4	13.5	509	298	marginal	746	good
RFD 0 – 250 ms (N/s)	4919 \pm 1286	0.86	0.77	0.95	9.6	7.5	13.6	458	265	marginal	663	good
IMP 0 – 300 ms (N.s)	344 \pm 108	0.92	0.82	0.96	9.4	8.8	16	33	22	marginal	55	good

Maximum force = gross force including body weight; PF = net force (excluding body weight); AlloPF = allometrically scaled PF; IMP 0 – 300 = impulse 0 – 300 ms sampling window; PF = absolute peak force; RFD 0 – 200 = rate of force development 0 – 200 ms sampling window; RFD 0 – 250 = rate of force development 0 – 250 ms sampling window; RPF (N/N) = PF relative to body weight, N/N; RFP (N/kg) = PF relative to body mass

Table 3. 2 Descriptive statistics for male and female participants for the ISqT and within session reliability variables attaining a criteria of an ICC ≥ 0.8 and a CV $\leq 10\%$

Variables	Mean \pm SD	ICC	95% CI		CV%	95% CI		TE	SWC (0.2)	Rating	SWC (0.5)	Rating
			Lower	Upper		Lower	Upper					
Maximum force (N)	2997 \pm 784	0.98	0.96	0.99	3.5	2.7	4.8	110	147	good	368	good
PF (N)	2322 \pm 709	0.97	0.94	0.99	4.6	3.6	6.4	110	131	good	327	good
RPF (N/N)	3.5 \pm 0.6	0.95	0.88	0.98	4.6	3.6	6.4	0.2	0.1	marginal	0.3	good
RPF (N/kg)	33.3 \pm 7.5	0.95	0.88	0.98	4.6	3.6	6.4	1.5	1.3	marginal	3.2	good
AlloPF (N/kg ^{0.67})	134.9 \pm 33.1	0.96	0.9	0.98	4.6	3.6	6.4	6.2	5.7	marginal	14.3	good
RFD 0 – 200 ms (N/s)	5879 \pm 1891	0.91	0.8	0.96	9.9	7.7	14	578	365	marginal	911	good
RFD 0 – 250 ms (N/s)	5083 \pm 1566	0.91	0.8	0.96	9.8	7.5	15.4	488	306	marginal	764	good
IMP 0 – 200 ms (N.s)	212 \pm 74	0.92	0.84	0.97	9.9	7.9	14.3	21	15	marginal	37	good
IMP 0 – 250 ms (N.s)	294 \pm 99	0.95	0.88	0.98	8.1	6.3	11.4	24	20	marginal	49	good
IMP 0 – 300 ms (N.s)	379 \pm 124	0.96	0.91	0.98	6.7	5.2	9.4	26	25	ok	62	good

Maximum force = gross force including body weight; PF = net force (excluding body weight); AlloPF = allometrically scaled PF; IMP 0 – 200 = impulse 0 – 200 ms sampling window; IMP 0 – 250 = impulse 0 – 250 ms sampling window; IMP 0 – 300 = impulse 0 – 300 ms sampling window; PF = absolute peak force; RFD 0 – 200 = rate of force development 0 – 200 ms sampling window; RFD 0 – 250 = rate of force development 0 – 250 ms sampling window. RPF (N/N) = PF relative to body weight, N/N; RFP (N/kg) = PF relative to body mass

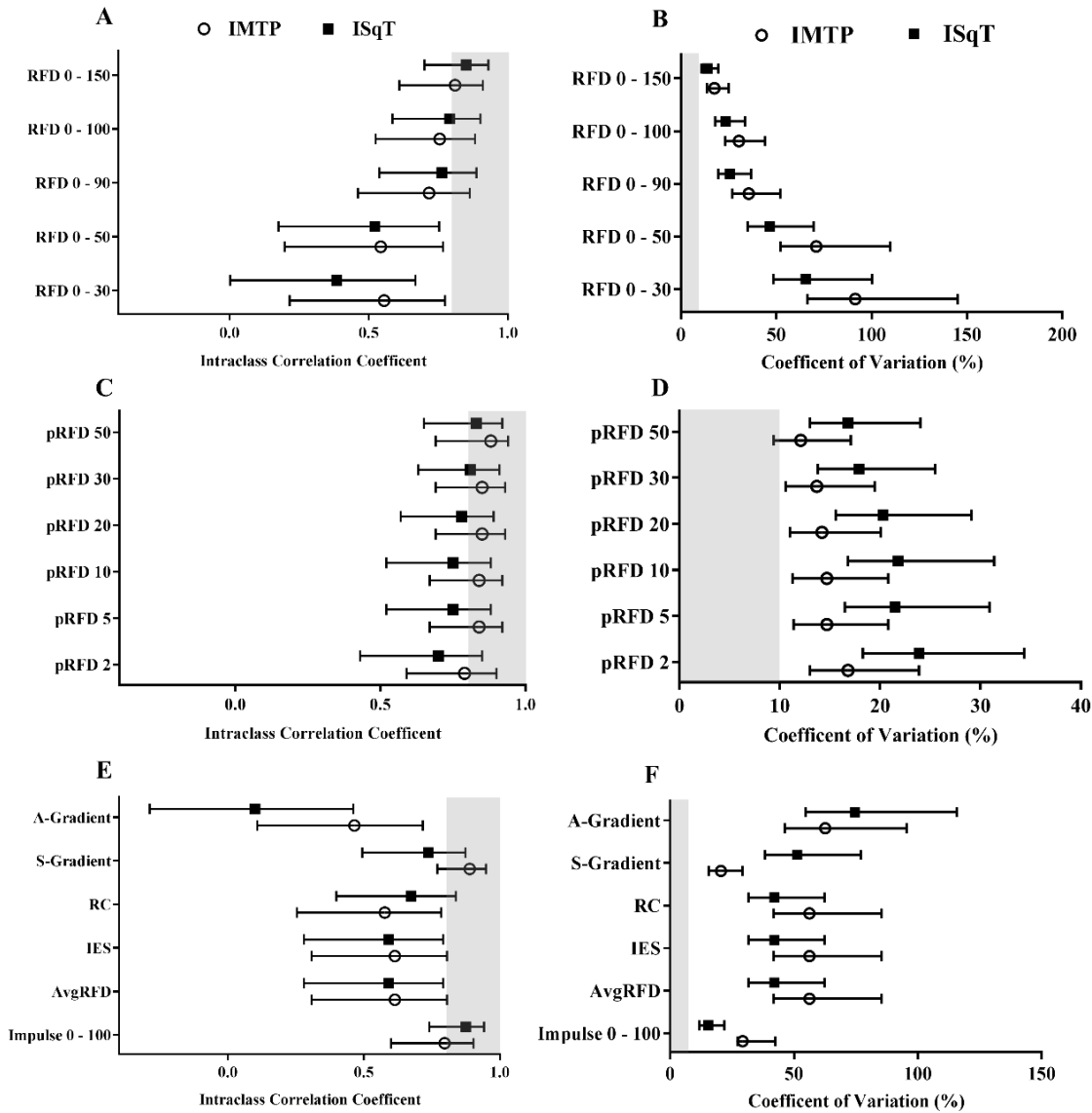


Figure 3.2 - Reliability measure of the ICC of the variables deemed unreliable in the IMTP and ISqT (ICC < 0.8 and/or CV > 10%).

Note: ○/■ = ICC/CV%; error bars indicate 95% confidence limits. Grey shaded area = zone of acceptable reliability (ICC ≥ 0.8 CV ≤ 10%). RFD = rate of force development; IMP = impulse. A = ICC RFD windows, B = CV%; avgRFD = average RFD; pRFD = peak RFD; RFD 0 - 150 = RFD 0 - 150 ms sampling window RFD 0 - 100 = RFD 0 - 100 ms sampling window; RFD 0 - 90 = RFD 0 - 90 ms sampling window; RFD 0 - 50 = RFD 0 - 50 ms sampling window; RFD 0 - 30 = RFD 0 - 30 ms sampling window. C = ICC pRFD windows, D = CV%: pRFD 50 = pRFD 50 ms sampling window; pRFD 30 = pRFD 30 ms sampling window; pRFD 20 = pRFD 20 ms sampling window; pRFD 10 = pRFD 10 ms sampling window; pRFD 5 = pRFD 5 ms sampling window; pRFD 2 = pRFD 2 ms sampling window. E = ICC IMP and Zatsiorsky RFD measures, F = CV%: RC = reactivity coefficient; IES = index of explosiveness; impulse 0 - 100 ms = IMP 0 - 100 ms sampling window

Differences between mean absolute PF, RPF (N/kg), AlloPF, RFD (0 – 200 ms), RFD (0 – 250 ms) and IMP (0 – 300 ms) produced during the IMTP and ISqT are detailed in Table 3.3. Holm’s Sequential Bonferroni adjusted *p*-values detail significant differences ($p < 0.05$) exist between absolute PF ($p = 0.006$), RPF ($p = 0.006$), AlloPF ($p = 0.006$) and IMP (0 – 300 ms) ($p = 0.036$) values between the IMTP and ISqT with the ISqT producing significantly higher results than the IMTP (Figure 3.3). Figure 3.4 details the magnitude of effect between the IMTP and ISqT. Participants were split by sex to determine if sex differences existed between tests. Among males, no significant differences were detected between any variable (Table 3.4). Among females, significant differences were observed between absolute PF ($p = 0.042$), RPF (N/kg) ($p = 0.042$) and AlloPF ($p = 0.042$) with the ISqT producing significantly ($p < 0.05$) higher results (Table 3.5). Figure 3.5 details differences individual and group mean values of the IMTP and ISqT for male and female participants for measures of absolute PF, AlloPF, RFD 0 – 250 ms and IMP 0 – 300 ms.

Table 3.3 Comparison of variables deemed reliable in the IMTP and ISqT for male and female participants

Variables	All Participants		95% CI	
	<i>p</i>	<i>g</i>	lower	upper
Absolute PF (N)	0.006*	0.52	-0.03	1.07
RPF (N/kg)	0.006*	0.74	0.18	1.30
AlloPF (N/kg ^{0.67})	0.006*	0.67	0.11	1.23
RFD 0 – 200 ms (N/s)	0.708	0.15	-0.39	0.69
RFD 0 – 250 ms (N/s)	0.708	0.11	-0.43	0.66
Impulse 0 – 300 ms (N.s)	0.036*	0.30	-0.25	0.84

*Statistically different using Holm’s Sequential Bonferroni adjusted *p*-value, *g* = Hedges *g* for magnitude of effect.

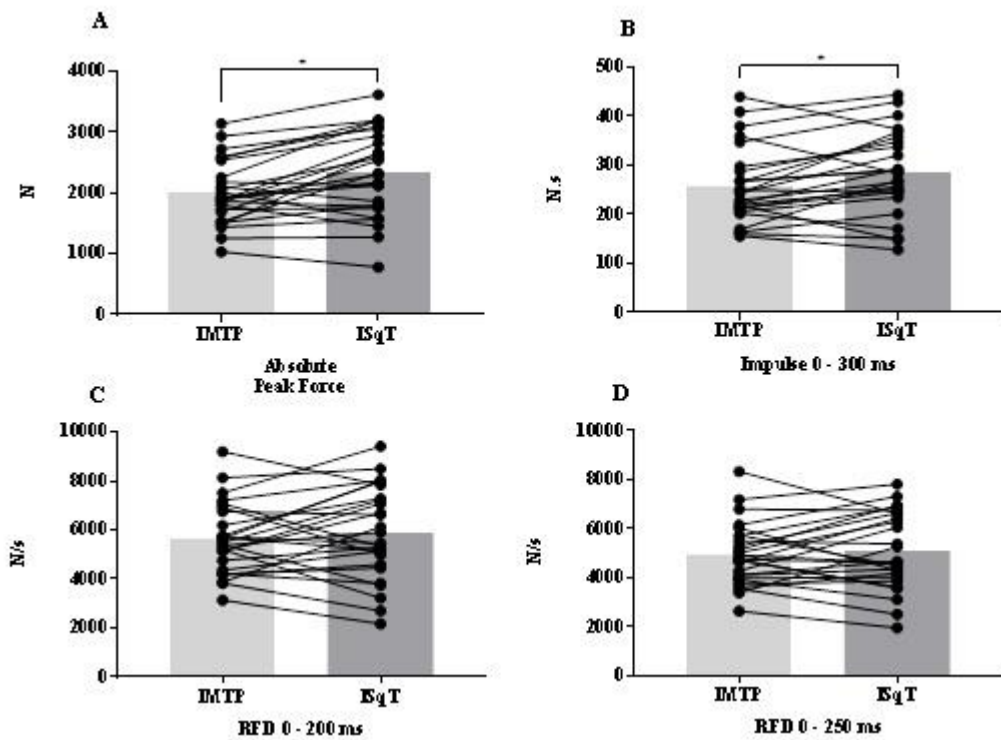


Figure 3.3 - Individual and group mean values of the IMTP and ISqT.

Note: A = absolute peak force, B = impulse 0 – 300 ms, C = RFD 0 – 200 ms, D = RFD 0 – 250 ms. Single dots represent the mean of the two trials of each participant for each test, straight line links to their corresponding score on the ISqT. *Significantly different using Holm’s Sequential Bonferroni adjusted p -value, $p < 0.05$.

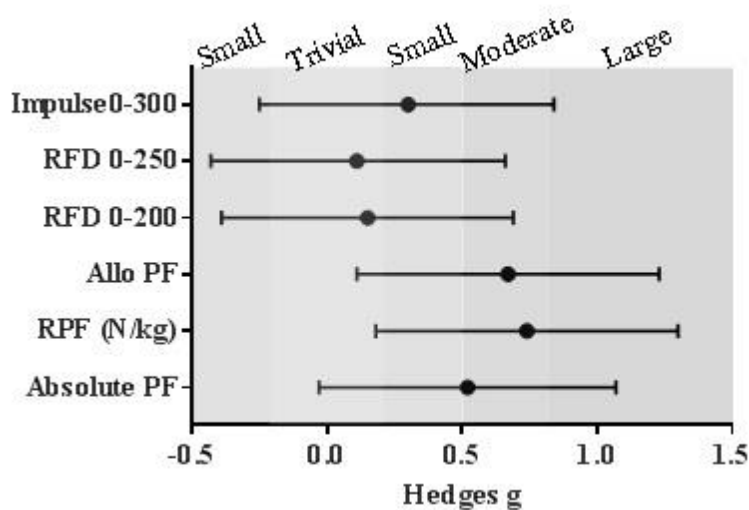


Figure 3.4 - Results of Hedges g with 95% CIs calculated for between tests.

Note: The shaded area detail Cohen’s scale which was interpreted as trivial ($g < 0.2$), small ($0.2 \leq g < 0.5$), moderate ($0.5 \leq g < 0.8$) and large ($g \geq 0.8$)

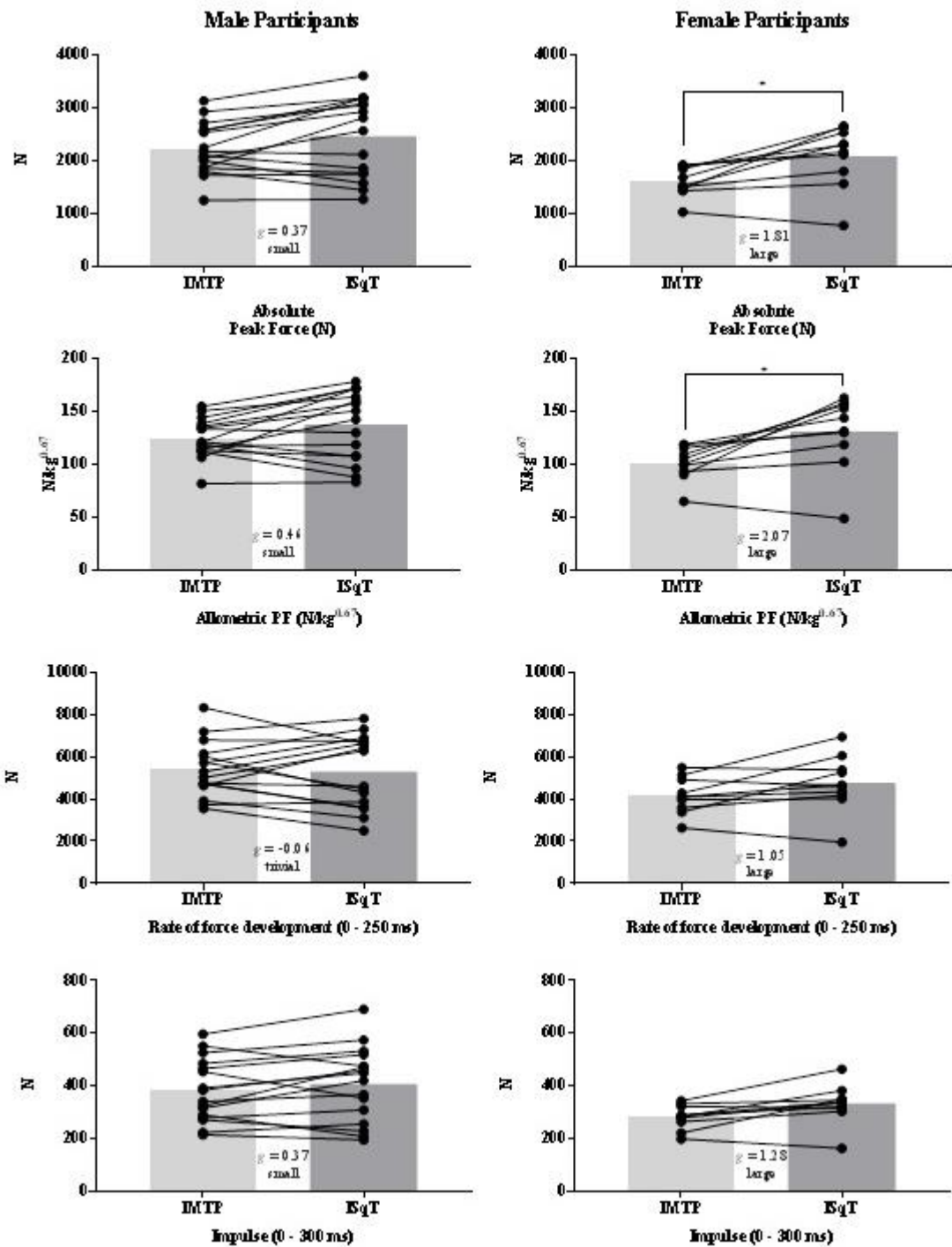


Figure 3.5 - Individual and group mean values of the IMTP and ISqT for male and female participants for measures of absolute PF, AlloPF, RFD 0–250 ms, and impulse 0–300 ms.

Note: Single dots represent the mean of the 2 trials of each participant for each test, straight line links to their corresponding score on the ISqT. g = Hedges' g to determine the magnitude of difference. AlloPF indicates allometrically scaled PF; impulse 0–300 ms, impulse 0- to 300-ms sampling window; IMTP, isometric mid-thigh pull; ISqT, isometric squat; PF, peak force; RFD 0–250 ms, RFD 0- to 250-ms sampling window. *Significantly different using Holm's sequential Bonferroni adjusted p value, $p < 0.05$.

Table 3.4 Descriptive statistics for male participants and comparison of variables deemed reliable in the IMTP and ISqT

Variables	IMTP	ISqT	<i>p</i>	<i>g</i>	95% CI	
	Mean ± SD	Mean ± SD			lower	upper
Absolute PF (N)	2225 ± 493	2466 ± 761	0.222	0.37	-0.33	1.07
RPF (N/kg)	30.4 ± 3.8	33.3 ± 7.0	0.245	0.50	-0.20	1.21
AlloPF (N/kg ^{0.67})	125 ± 18.5	137.6 ± 33	0.245	0.46	-0.25	1.16
RFD 0 – 200 ms (N/s)	6077 ± 1502	6044 ± 2090	1.000	-0.02	-0.71	0.68
RFD 0 – 250 ms (N/s)	5392 ± 1301	5297 ± 1701	1.000	-0.06	-0.75	0.63
Impulse 0 – 300 ms (N.s)	383 ± 119	407 ± 142	0.555	0.18	-0.52	0.87

Table 3.5 Descriptive statistics for female participants and comparison of variables deemed reliable in the IMTP and ISqT

Variables	IMTP	ISqT	<i>p</i>	<i>g</i>	95% CI	
	Mean ± SD	Mean ± SD			lower	upper
Absolute PF (N)	1624 ± 285	2090 ± 578	0.042*	1.81	0.77	2.85
RPF (N/kg)	26 ± 4.1	33.4 ± 8.7	0.042*	2.06	0.98	3.15
AlloPF (N/kg ^{0.67})	101.6 ± 16.3	130.6 ± 34.6	0.042*	2.07	0.98	3.15
RFD 0 – 200 ms (N/s)	4895 ± 1049	5614 ± 1589	0.156	1.10	0.16	2.04
RFD 0 – 250 ms (N/s)	4162 ± 857	4741 ± 1335	0.156	1.05	0.11	1.98
Impulse 0 – 300 ms (N.s)	283 ± 46	333 ± 75	0.051	1.28	0.32	2.25

*Statistically different using Holm’s Sequential Bonferroni adjusted p-value, *g* = Hedges *g* for magnitude of effect

3.6 Discussion

The aim of this study was to determine the reliability of the IMTP and ISqT performed at the same knee and hip angles, define the usefulness of the tests and determine the magnitude of effect between the IMTP and ISqT among male and female athletes and report reference TE and SWC values. The hypothesis that the IMTP and ISqT would be reliable for the same variables and PF being able to detect changes in performance can be accepted and the hypothesis that the ISqT would produce greater measures of force in both male and female athletes can be rejected as only female athletes produced greater force in the ISqT. This study provides new information on the reliability and usefulness of both tests and the mean values produced at the same knee and hip angle. Variables that were reliable in both tests include, maximum force, absolute PF, RPF (N/N) and (N/kg), AlloPF, RFD (0 – 200 ms and 0 – 250 ms) and IMP (0 – 300 ms) ($ICC \geq 0.8$ and $CV \leq 10\%$). IMP (0 – 200 ms) and (0 – 250 ms) were deemed reliable in the ISqT. All short sampling windows of RFD (up to 150 ms), pRFD (up to 50 ms), IMP (0 – 100 ms), IES, RC, S-gradient and A-gradient were deemed unreliable for both tests.

PF has been reported as the most reliable variable measured during an IMTP. Previous research reported ICCs ≥ 0.92 and $CV \leq 5\%$ (Beckham *et al.* 2014, Haff *et al.* 2015, Thomas *et al.* 2015a, Thomas *et al.* 2015b), which is similar to the results of this study. However, differences exist in the definition of PF with some research including body weight in the calculation and other research calculating PF as maximum force minus body weight. Beckham *et al.* (2013) included body weight in their calculation whereas West *et al.* (2011) calculated PF minus the participant's body weight. Some research does not clearly state whether body weight was included (Stone *et al.* 2004) leaving the interpretation of results confounding for coaches. Previous research has reported that RFD measures (0 – 200 ms and pRFD) are reliable with $ICC > 0.8$ even though the $CV > 15\%$ (Beckham *et al.* 2014, Thomas *et al.* 2015b). Haff *et al.* (2015) reported RFD sampling windows from 0 – 30 ms up to 0 – 250 ms as reliable ($ICC \geq 0.80$ and a $CV \leq 10\%$), different to the results reported in this study. Maffioletti *et al.* (2016) noted when measuring RFD, familiarisation is very important and prolonged practice procedures may be

required to obtain reliable data. The participants used in the study by Haff *et al.* (2015) (collegiate volleyball players) regularly performed the IMTP and had a lot of experience in producing force in the second pull position. The participants used in this study however, were performing the test for the first time during familiarisation and this may explain the difference in results. To achieve reliable data for RFD measures, additional familiarisation sessions may be required. Additionally, the method for detecting the onset of contraction used in the study by Haff *et al.* (2015) was different and this may impact reliability. Haff *et al.* (2015) visually identified the start point and in this study the point was defined at the point where the force exceeded 5 SDs from baseline. Haff *et al.* (2015) deemed pRFD sampling windows unreliable except for pRFD 20, however the CV was 12.9%, which would be unreliable based on the criteria set in this study. All measures of pRFD were deemed unreliable in this study. Similar to the results of this study, Haff *et al.* (2015) deemed avgRFD unreliable. IMP at 100 ms, 200 ms and 300 ms has been reported as reliable in previous research ($ICC \geq 0.86$ and $CV \leq 8.4\%$) (Beckham *et al.* 2014, Thomas *et al.* 2015a, Thomas *et al.* 2015b), in line with the results of this study, except for IMP at 100 ms which was deemed unreliable.

The TE was less than the $SWC_{0.2}$ for maximum force and absolute PF in both tests, and in the IMTP, the TE of RPF (N/kg) was less than $SWC_{0.2}$ demonstrating that the test is useful in detecting if a “meaningful change” in performance has occurred for these variables. All other variables in both tests were rated as “marginal” or “ok”. The TE was below the $SWC_{0.5}$ for each variable for each test rating the usefulness as “good”. Where the TE is above the $SWC_{0.2}$, coaches and practitioners can use $SWC_{0.5}$ to provide context of “meaningful change” to group analysis since the $SWC_{0.2}$ may lack the sensitivity.

Participants produced significantly greater absolute PF, RPF (N/kg) and AlloPF in the ISqT compared to the IMTP with a moderate effect size. In addition, participants also produced significantly greater IMP (0 – 300 ms) with a small effect size. However, when participants were split by sex, there were no significant differences for males, also having a small effect size. By comparison, significant differences were seen for female participants for

absolute PF, RPF (N/kg) and AlloPF with a large effect size. Results are similar to Nuzzo *et al.* (2008) who reported that males produced an additional 12.5% RPF (N/kg) in an ISqT. Males produced an additional 9.5% RPF and females produced an additional 28.5% RPF during an ISqT compared with the IMTP. This may be due to the elimination of the use of upper extremity force during the ISqT compared with the IMTP, providing a potential advantage to athletes with weakness or dysfunction in their upper extremity. Females have reported to be weaker in the upper extremity compared to their male counterparts (Yanovich *et al.* 2008), possibly leaving females at a disadvantage in demonstrating lower extremity strength when performing an IMTP compared to the ISqT. In addition, participants in this study had at least 6 months of resistance training experience, and not all were familiar with weightlifting movements. More recently, Beckham *et al.* (2018) noted that those with less experience in weightlifting movements have spent less time overloading the power position and would not be expected to express the effect of training in this position. This lack of experience in this position may also affect the reliability results (Beckham *et al.* 2018). For example, individual variation is present in the data, some athletes scored higher on the IMTP compared to the ISqT, with other athletes scoring higher on the ISqT compared to the IMTP (Figures 3.3 and 3.5). This may be due to the differences in training background of the athletes used in this study. Some athletes performed Olympic lifting in training. Therefore, they would be used to producing force in this position. However, some athlete did not perform Olympic lifting, and this may be the reason they had higher scores in the ISqT compared to the IMTP. Further research should identify if the athletes training background has an effect on the ability to produce force in each test.

Results suggest that the IMTP and ISqT are reliable for comparable variables, with the IMTP appearing to be more reliable when examining pRFD and the ISqT more reliable when examining IMP. When determining the reliability, the ICC and CV should be measured with the CIs giving a clearer understanding of the level of reliability. Significant differences exist between the IMTP and ISqT, and this difference is greater for female athletes compared to males.

3.7 Practical Applications

The present study demonstrated that the IMTP and ISqT are reliable for maximum force, absolute PF, RPF, RFD (0 – 200 ms and 0 – 250 ms) and IMP (0 – 300 ms). IMP (0 – 200 ms and 0 – 250 ms) is reliable in the ISqT. Variables of maximum force and absolute PF are useful in detecting meaningful change in both tests ($SWC_{0.2}$). Where the TE is above the $SWC_{0.2}$, coaches and practitioners can use $SWC_{0.5}$ to provide context of “*meaningful change*” for all other variables in both tests. Significant differences exist between the IMTP and ISqT for measures of absolute PF, RPF, AlloPF and IMP (0 – 300 ms). If coaches and practitioners are looking to measure an athlete’s true maximum strength, the ISqT may be the preferred test, especially among female athletes. The ISqT may be a truer reflection of the athlete’s maximum lower extremity strength compared with the IMTP. Future research should determine if different knee and hip angles in the ISqT produce higher forces than those used in this study. Previous research has used different knee and hip angles in the ISqT than those used in this study (Brady *et al.* 2018a) but no previous research has compared the amount of force produced at the different positions.

3.8 Conclusions

Results suggest that the IMTP and ISqT are reliable for maximum force, absolute PF, RPF, RFD (0 – 200 ms and 0 – 250 ms) and IMP (0 – 300 ms). The ISqT may be useful for measures of IMP. Both tests are useful in detecting the SWC for maximum force and absolute PF. The ISqT produces significantly higher absolute and RPF among female athletes.

Chapter 4: Study 3 - The Relationship between Isometric Strength and Sprint Acceleration in Sprinters

Brady, C.J., Harrison, A.J., Flanagan, E.F., Haff, G.G., Comyns, T.M. 2019.
The relationship between isometric strength and sprint acceleration in
sprinters. *International Journal of Sports Physiology and Performance* (In
Press).

4.1 Preface

Having determined the reliability of the IMTP and ISqT on the isometric testing system, I moved towards the second aim of the thesis; to determine the relationship between isometric strength and sprint acceleration performance. Previous research has established relationships between isometric measures of strength and sprint performance in field sports, and one paper had examined the relationship among sprinters. However, the paper examining the sprinters, did not examine the 0 – 5 m segment of the sprint or fully diagnose the force-time curve. Study 2 detailed that female athletes produced significantly greater PF during the ISqT compared with the IMTP, therefore both tests were included in analysis. Further, no paper had examined the relationship between the ISqT and sprint performance in sprinters. In addition, I examined if isometric measures of strength are able to predict sprint performance and determined what variable has the greatest influence on sprint performance. With a wide variety of strength tests available for coaches to choose from, coaches need to understand how strength qualities differ, to target training appropriately. Based on the results, I include practical applications for coaches on the uses and limitations of isometric strength testing for sprint athletes.

4.2 Abstract

Purpose: This investigation examined the relationships between the IMTP, ISqT and sprint acceleration performance in track and field sprinters, and determined whether there are differences between male and female sprinters.

Methods: Fifteen male and ten female sprinters performed 3 maximal effort IMTPs, ISqTs and 3 by 30 m from blocks. **Results:** Among males, results detailed large or very large correlations between IMTP and ISqT PF, RPF, force at 100, 150 and 200 ms, RFD (0 – 150, 0 – 200 ms) and IMP (0 – 200 ms) and 0 – 5 m time ($r = -0.517$ to -0.714 ; $p < 0.05$). IMTP IMP significantly predicted 0 – 5 m time ($B = -0.582$, $p = 0.023$). ISqT RPF significantly predicted 0 – 5 m time ($B = -0.606$, $p = 0.017$). Among females, small or moderate correlations were observed between IMTP or ISqT variables and sprint times. Males measured significantly higher than females for all IMTP

measures except for RPF. Males were significantly faster than females at all splits. When comparing measures of the ISqT, there were no significant differences between males and females. **Conclusions:** Variables measured during the IMTP and ISqT largely or very largely correlated with 0 – 5 m sprint performance in male athletes. On examination of the 95% unstandardised B coefficients, isometric strength can have a sizable influence on 0 – 5 m time (-0.22 s) but in some cases the maximum effect could be very small (-0.02 s).

4.3 Introduction

Successful performance in sprint events requires rapid acceleration and a high maximum velocity. The starting block phase and subsequent acceleration phase are important phases, which directly generate the results in a 60 m and 100 m sprint (Slawinski *et al.* 2010). During the acceleration phase, an athlete's expression of strength will change, for example, jump height measured during a squat jump (SJ) and CMJ moderately or largely correlates with acceleration from the 5th to 11th steps, and reactive strength measured through a repeat ankle jumps moderately or largely correlates with acceleration from the 14th to the 19th steps (Nagahara *et al.* 2014). On examination of the sprint start, Slawinski *et al.* (2010) concluded that sprinters with greater “explosive strength” were able to generate a greater RFD and IMP and thus a greater velocity from the starting blocks to the toe-off of the second step. Therefore, a sprinters absolute strength and ability to express forces rapidly are key feature of their ability to accelerate efficiently. Additionally, the mechanical outputs of world class sprinters during the acceleration phase are greater in males than females, with women also having a shorter acceleration phase, therefore these strength qualities could be different between males and females (Slawinski *et al.* 2017).

Maximum strength has been defined as the ability to produce maximum force against an external resistance (Stone 1993). The IMTP and ISqT are two tests commonly used to test an athlete's maximum strength capabilities and these tests can measure variables such as PF, RFD and IMP (Brady *et al.* 2018a). The relationship between maximum strength measured during the IMTP/ISqT

and sprint performance has been examined among male soccer and rugby players (West *et al.* 2011, Tillin *et al.* 2013, Wang *et al.* 2016). There appears to be large correlations between IMTP PF and sprint times over 5 m ($r = -0.57$) and 20 m ($r = -0.69$) amongst collegiate male soccer and Rugby League players (Thomas *et al.* 2015a). Further, large correlations ($r = \sim -0.5$ to -0.7) have been reported between pRFD and sprint times over 5 m (Thomas *et al.* 2015a, Wang *et al.* 2016), 10 m (West *et al.* 2011) and 20 m (Thomas *et al.* 2015a) among soccer and rugby players. Additionally, Wang *et al.* (2016) reported a large correlation between sprint time over 5 m and RFD 0 – 30 ms ($r = -0.57$) and RFD 0 – 50 ms ($r = -0.53$). Amongst a group of athletes from various sports, Conlon *et al.* (2013) reported that IMTP PF and pRFD moderate and large correlations with 5 m ($r = -0.58$ and -0.49 respectively), 10 m ($r = -0.61$ and -0.5 , respectively), 20 m ($r = -0.61$ and -0.47 respectively) and 30 m ($r = -0.61$ and -0.46 respectively) sprint times. Tillin *et al.* (2013) is the only study to the authors' knowledge to examine the relationship of ISqT force measures and sprint times among rugby players. Results reported that sprint times were related to early phase ISqT force (≤ 100 ms) normalised to maximal force (i.e., expressed as a percentage of maximal force) (5 m, $r = -0.63$, $p = 0.005$ and 20 m, $r = -0.54$, $p = 0.002$).

While negative correlations between isometric force production and sprint performance have been reported, sprinters differ from field sport athletes in their start position. Field sport athletes start from various positions such as rolling or jogging starts, whereas sprinters start their race from starting blocks, which requires a high technical ability to apply optimum vertical and horizontal force (Slawinski *et al.* 2010). Wild *et al.* (2018) compared sprinter and rugby players acceleration technique and detailed that there were multiple difference in the magnitudes of various touchdown and toe-off kinematics between groups. It is difficult to assess sports specific variables among a group of sprint athletes as participants generally end up being either a large heterogeneous group (Conlon *et al.* 2013) (one hundred and thirty nine male and female athletes were recruited from various sports including track and field, soccer, gymnastics etc.) or a smaller more homogeneous group (Kümmel *et al.* 2016) (five male and female elite sprinters). Recently, Healy *et al.* (2018) reported moderate relationships between IMTP PF and RPF and

sprint performance over 40 m with 10 m splits, among a group of twenty eight national and international level sprinters. The authors did not measure 0 – 5 m or fully diagnose the force-time curve, examining measures of strength such as RFD or IMP. Further, no paper has examined the relationship between ISqT force measures of strength and sprint performance in sprint athletes. There is a lack of studies that include a representative sample of high-level sprinters performing isometric strength tests that assess various strength qualities to help identify the best correlations of speed performance. This information could assist coaches in choosing appropriate tests for use in monitoring training effects and identifying strengths and weaknesses in the athlete's strength profile, which would help in programme design. Therefore, the primary aim of the current study was to assess the relationship between isometric measures of strength (IMTP and ISqT) and sprint acceleration performance in male and female sprinters. It was hypothesised that IMTP and ISqT variables would relate to 0 – 5 m sprint performance.

4.4 Methods

4.4.1 Participants

Fifteen male (21.7 ± 3.6 years, 1.81 ± 0.05 m and 75.9 ± 5.8 kg) and ten females (23.9 ± 2.3 years, 1.67 ± 0.05 m and 64.4 ± 5.5 kg) sprint athletes took part in this study. Among the females there were two 100 m sprinters (personal best (pb) = 11.66 ± 0.04 s), four 100 mH (pb = 13.67 ± 0.21 s), three 200 m sprinters (pb = 23.70 ± 0.28 s) and one 400 m sprinter (pb = 53.26 s). Among the males, there were nine 100 m sprinters (pb = 10.92 ± 0.22 s), four 110 mH (pb = 14.1 ± 0.23 s) and two 400 m sprinters (pb = 48.43 ± 0.14 s). All athletes had at least two years' experience of sprint and strength training. All participants provided written informed consent prior to participation. The study was approved by the Institutions Research Ethics Committee.

4.4.2 Study Design

A cross-sectional study design was undertaken to assess the relationship between isometric strength and sprint acceleration performance. All participants took part in a familiarisation session for the IMTP and ISqT one

week prior to the testing session. On the day of testing, participants completed a general warm up, an isometric specific warm up, maximal effort IMTPs and ISqTs in a randomised order followed by an individualised sprint warm up and 3 by 30 m sprints from blocks.

4.4.3 Methodology

Participants took part in a familiarisation session for the IMTP and ISqT after an explanation of the study and signing of the informed consent. One week later, participants completed the testing session following a 48-hour rest. The order sequences of isometric tests were randomised among participants to limit possible effect of potentiation and fatigue. Participants had 5 minutes' rest between the two isometric tests.

Participants completed a general warm-up consisting of 3 minutes of cycling, 10 bodyweight squats, 10 bodyweight walking lunges and 10 gluteal bridge exercises. They then completed the isometric specific warm-up for the first test to be completed as previously reported in the literature (Brady *et al.* 2018b), consisting of pulling/pushing the bar for 5 seconds at a self-directed 50%, 3 seconds at 70% to 80% and 3 seconds at 90% of maximal effort with 1-minute recovery between efforts. Participants then rested for 2 minutes before completing their maximum efforts.

For the IMTP, participants were set in the correct position, replicating the body position at the beginning of the second pull position of the clean or snatch (adopting sagittal knee angles of $141^{\circ} \pm 4^{\circ}$ and hip angles $138^{\circ} \pm 2^{\circ}$). This position is the strongest and most powerful position during weightlifting movements, generating the highest forces and velocities of any part of the lift (Garhammer 1993). Feet were placed between hip- and shoulder-width apart with the toes pointed slightly outward. Angles were measured using a hand-held goniometer; grip and foot width were measured and remained consistent between trials. Participants used lifting straps to standardise grip strength (Brady *et al.* 2018b). Participants were required to maintain their position throughout the test. Participants completed 3 maximal efforts with each effort lasting 5 seconds with a 2-minute rest between trials. For each trial participants were instructed to “pull as hard and as fast as you can” to ensure

maximal force was achieved. Participants were instructed to get ready, and then were given a countdown of “3, 2, 1, pull!”. Verbal encouragement was provided during each trial. Participants completed a fourth trial if they lost their position, grip or the effort was not deemed maximum effort, or if there was a greater than 250 N difference between efforts (Kraska *et al.* 2009). The procedure used for the ISqT was the same as that for the IMTP, with the exception that participants were instructed to “push” instead of “pull” and lifting straps were not required. The knee and hip angles used in the IMTP were replicated for the ISqT, to compare isometric strength in the same position. While the knee and hip angles used for the IMTP were clearly defined (Haff *et al.* 2015), the sagittal knee angles used for the ISqT ranged from 90 - 150° (Brady *et al.* 2018a).

All isometric testing was conducted on a custom-made isometric rack (Sorinex inc., Lexington, SC), allowing the placement of the bar at 0.5 cm intervals and permitting the desired position for each participant. The rack was anchored to the floor and placed over a Kistler 9287 CA force platform (Winterthur, Switzerland), sampling at 1000 Hz. The collection period for each trial was set at 12 seconds, and a baseline was measured during the 3-second countdown prior to the initiation of the pull (Brady *et al.* 2018b). The criterion onset threshold and onset of the contraction were defined as the point where the force exceeded 5 SD from baseline (Dos’Santos *et al.* 2017a). PF was reported as maximum force generated during the 5 second trial minus the participant’s body weight. PF was also reported relative to body mass (N/kg). Since contact times during sprinting range from ~ 100 – 200 ms (Mero *et al.* 1992), these limits were used when selecting isometric variables of time specific force epochs, RFD and IMP. Force at 100, 150 and 200 ms from the initiation of the pull was therefore determined to align with the contact times in sprinting. RFD was calculated ($\Delta\text{Force}/\Delta\text{Time}$) and was applied to specific time bands (0 – 100, 0 – 150 and 0 – 200 ms) previously reported in the literature (Haff *et al.* 2015). IMP was determined as average force divided by the change in time over 100 and 200 ms.

After a ten-minute rest, participants then completed an individualised race-specific warm up lasting ~30 minutes, including 2 by 15 m starts from blocks. All participants completed 3 maximal effort 30 m sprints from a block start

with six minutes of recovery between sprints. Dual-beam timing gates (Microgate, Bolzano, Italy) were positioned at 5, 10, 20 and 30 m. Split times from 0 – 5 m, 5 – 10 m, 10 – 20 m, 20 – 30 m and overall 30 m were recorded. Timing was initiated at the instant the athletes hand left the track surface using a previously validated protocol that synchronised timing gates to the Optojump system, which is an optical measuring unit (Healy *et al.* 2016b).

4.4.4 Statistical Analyses

All force-time data were analysed using a custom spreadsheet to determine specific force–time characteristics. Normality was assessed for all variables using the Shapiro-Wilk statistic. All variables were normally distributed ($p > 0.05$). Relationships between isometric strength variables and sprint times were determined by Pearson product-moment correlation using SPSS software (version 22.0, IBM Corp, Armonk, NY). The best repetitions based on isometric PF and 30 m sprint time were used for analysis (Beattie *et al.* 2017b). Correlations were evaluated as: small (0.1–0.29), moderate (0.3–0.49), large (0.5–0.69), very large (0.7–0.89), nearly perfect (0.9–1.0), and perfect (1.0) (Hopkins *et al.* 2009). Reliability for isometric variables was calculated by determining the CV, calculated as the TE and expressed as a CV% and the ICC and 95% CIs using a Microsoft Excel spreadsheet (Hopkins 2015). Acceptable reliability was determined at an ICC ≥ 0.8 and a CV $\leq 10\%$ (Hopkins 2000). Based on the 95% CI of the ICC estimate, values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.90 are indicative of poor, moderate, good, and excellent reliability, respectively (Koo and Li 2016).

To determine if differences in IMTP and ISqT strength and sprint times existed between male and female groups, two-tailed independent-samples *t* tests were reported with Holm’s sequential Bonferroni method (Holm 1979). Effect sizes were calculated (Hedges *g*) to determine the magnitude of differences between groups. The magnitude of Hedges’ *g* was interpreted using Cohen’s scale as trivial ($g < 0.2$), small ($0.2 \leq g < 0.5$), moderate ($0.5 \leq g < 0.8$) and large ($g \geq 0.8$) (Cohen 1988).

To determine if isometric strength could predict sprint performance among male sprinters, the contribution of RPF, RFD 0 – 200 ms and IMP 0 – 200 ms on sprint time (dependent variable) was then evaluated using a backward stepwise regression analysis for the ISqT. In a separate regression analysis, RFD 0 – 200 ms and IMP 0 – 200 ms were analysed for the IMTP. The high correlation between RPF and IMP ($r = 0.932$) indicated collinearity. Given the known determinative link between IMP and change in velocity based on Newtons 2nd law, it is clear that RPF was collinear with IMP and was therefore removed from the analysis. The variables were assessed for homoscedasticity using a P-P Plot, independent errors using the Durbin & Watson test (Durbin Watson = 1.612) (Durbin and Watson 1950), and multicollinearity using variance-inflation-factor (VIF) method (VIF = 1.00). The criterion for statistical significance was set at $p \leq 0.05$.

4.5 Results

The results of the reliability analysis for IMTP and ISqT measures are presented in Table 4.1. All measures displayed acceptable reliability with ICCs above 0.92 and CVs below 9.6% except for IMP (0 – 100 ms) and RFD (0 – 100 ms), which were deemed unreliable in both tests. All reliable variables had ‘good’ or ‘excellent’ reliability based on the lower bound 95% confidence interval (Koo and Li 2016). Descriptive statistics (mean \pm SD) for all isometric strength variables and sprint splits, and differences between male and female athletes are presented in Table 4.2. The sprint times achieved by athletes in this study are slow, partly due to the timing gate method used, where the timing was initiated when the participants hand left the start pad. The more common method is when participants break the timing gate at the zero mark, but have already increased their velocity as they move through the timing gates. The difference in methods would account for the slower times observed in this study. Males measured significantly higher than females for all IMTP measures except for RPF. Males were significantly faster than females at all splits (Figure 4.1). However, when comparing measures of the ISqT, there were no significant differences between males and females. Among males, the 0 – 5 m split was very largely correlated with 0 – 30 m

time, and other splits only reported small or moderate correlations with 0 – 30 m time. Among female sprinters, all splits largely, very largely or nearly perfectly correlated with each other (Table 4.3).

Table 4.1 Within session reliability variables attaining a criteria of an ICC ≥ 0.8 and a CV $\leq 10\%$ with 95% confidence intervals

Variable	IMTP		ISqT	
	ICC	CV%	ICC	CV%
PF (N)	0.98 (0.96 – 0.99)	4.7 (3.6 – 6.6)	0.99 (0.97 – 0.99)	4.0 (3.1 – 5.7)
RPF (N/kg)	0.98 (0.95 – 0.99)	4.7 (3.6 – 6.6)	0.98 (0.97 – 0.99)	4.0 (3.1 – 5.7)
Force at 100 ms (N)	0.92 (0.83 – 0.96)	9.1 (7.1 – 13)	0.97 (0.93 – 0.99)	9.6 (7.4 – 13.7)
Force at 150 ms (N)	0.96 (0.92 – 0.98)	5.6 (4.3 – 7.8)	0.97 (0.93 – 0.99)	6.8 (5.3 – 9.6)
Force at 200 ms (N)	0.97 (0.93 – 0.99)	5.3 (4.1 – 7.5)	0.96 (0.92 – 0.98)	6.5 (5.0 – 9.1)
RFD 0 – 150 ms (N/s)	0.92 (0.83 – 0.96)	8.8 (6.8 – 12.4)	0.94 (0.87 – 0.97)	9.3 (7.2 – 15.2)
RFD 0 – 200 ms (N/s)	0.94 (0.86 – 0.97)	7.2 (5.6 – 10.1)	0.94 (0.87 – 0.97)	8.3 (6.4 – 11.8)
IMP 0 – 200 ms (N.s)	0.96 (0.92 – 0.98)	6.1 (4.7 – 8.6)	0.97 (0.92 – 0.98)	7.8 (6.1 – 11.0)

PF = peak force; IMP = impulse; RFD = rate of force development; RPF = relative peak force. Results are presented as ICC/CV (95% CI)

Table 4.2 Descriptive statistics for male and female participants for the IMTP, ISqT and sprint split times and comparison of variables between male and female participants

Variable	Males	Females	<i>p</i> value	ES
IMTP PF (N)	2070 (548)	1420 (400)	0.016*	1.27
ISqT PF (N)	2314 (646)	1884 (521)	0.581	0.69
IMTP RPF (N/kg)	27.3 (7.2)	21.9 (5.4)	0.057	0.85
ISqT RPF (N/kg)	30.6 (8.6)	29.2 (7.4)	0.679	0.17
IMTP force at 100 ms (N)	1186 (292)	837 (347)	0.024*	1.07
ISqT force at 100 ms (N)	1193 (446)	897 (339)	0.581	0.70
IMTP force at 150 ms (N)	1463 (312)	988 (320)	0.008*	1.46
ISqT force at 150 ms (N)	1395 (2386)	1179 (412)	0.581	0.72
IMTP force at 200 ms (N)	1612 (365)	1067 (302)	0.008*	1.54
ISqT force at 200 ms (N)	1660 (437)	1380 (442)	0.581	0.62
IMTP RFD (0 – 150 ms) (N/s)	7527 (1594)	5337 (2136)	0.021*	1.16
ISqT RFD (0 – 150 ms) (N/s)	7395 (2386)	5805 (1869)	0.581.	0.70
IMTP RFD (0 – 200 ms) (N/s)	6392 (1459)	4401 (1497)	0.015*	1.31
ISqT RFD (0 – 200 ms) (N/s)	6351 (1725)	5360 (1544)	0.581	0.58
IMTP IMP (0 – 200 ms) (N.s)	220 (51)	149 (48)	0.012*	1.38
ISqT IMP (0 – 200 ms) (N.s)	225 (70)	173 (63)	0.560	0.75
0 – 5 m split (sec)	1.187 (0.048)	1.263 (0.033)	< 0.0001*	1.70
5 – 10 m split (sec)	.701 (0.023)	.744 (0.026)	< 0.0001*	1.70
10 – 20 m split (sec)	1.167 (0.032)	1.263 (0.034)	<0.0001*	2.79
20 – 30 m split (sec)	1.078 (0.026)	1.168 (0.032)	< 0.0001*	3.05
0 – 30 m (sec)	4.133 (0.102)	4.437 (0.112)	< 0.0001*	2.77

IMP = impulse; IMTP = isometric mid-thigh pull; ISqT = isometric squat; PF = peak force; RFD = rate of force development; RPF = relative peak force. Results are presented as mean (SD). *Between-groups differences significantly different presented in bold using Holm's sequential Bonferroni adjusted *p* value, *p* < 0.05

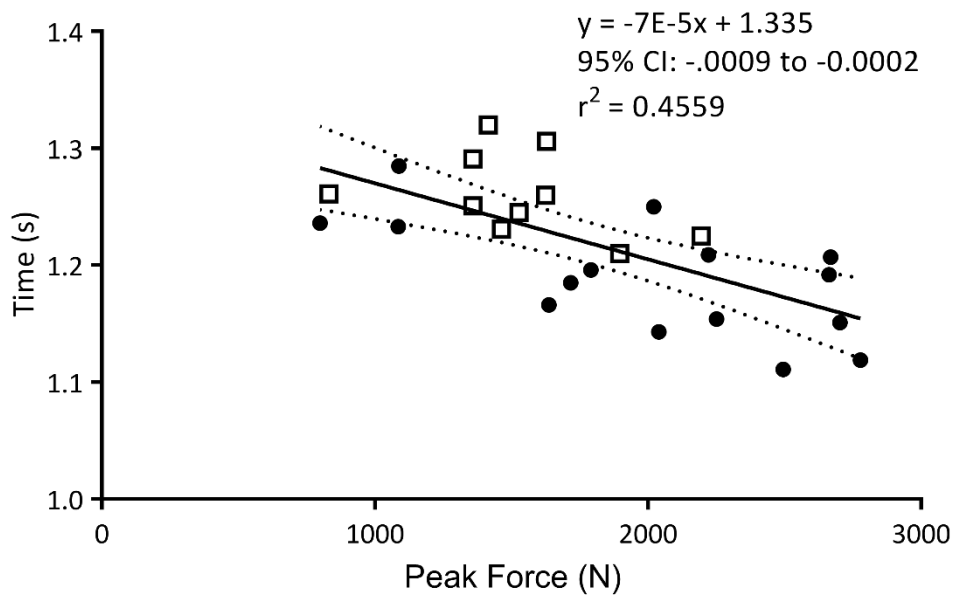


Figure 4.1 - Scatter plot correlative findings with 95% CIs between IMTP peak force (N) and 0 – 5 m time.

Note: Dashed line represents 95% CIs (1.277 – 1.393). Circle marker = male athletes, square marker = female athletes

Table 4.3 Inter-correlation matrix between time splits in males (top) and females (bottom)

	0 – 5 m	5 – 10 m	10 – 20 m	20 – 30 m	0 – 30 m
Males					
0 – 5 m	1*				
5 – 10 m	0.029 (-0.347 to 0.382)	1*			
10 – 20 m	0.459 (0.03 to 0.774)	0.683** (0.379 to 0.896)	1*		
20 – 30 m	0.382 (-0.165 to 0.707)	0.738** (0.507 to 0.902)	0.914** (0.778 to 0.978)	1*	
0 – 30 m	0.719** (0.378 to 0.907)	0.644** (0.279 to 0.838)	0.919** (0.799 to 0.978)	0.889** (0.725 to 0.955)	1*
Females					
0 – 5 m	1*				
5 – 10 m	0.632* (-0.031 to 0.955)	1*			
10 – 20 m	0.718* (0.441 to 0.983)	0.563 (-0.203 to 0.938)	1*		
20 – 30 m	0.736* (0.283 to 0.976)	0.804** (0.370 to 0.961)	0.886** (0.704 to 0.978)	1*	
0 – 30 m	0.871** (0.604 to 0.993)	0.821** (0.248 to 0.983)	0.903** (0.704 to 0.978)	0.962** (0.918 to 0.994)	1*

Results are presented as r (95% CI). Statistically significant correlations are presented in bold. * $p \leq 0.05$, ** $p \leq 0.01$

4.5.1 Relationship Between Isometric Strength and Sprint Performance

Pearson correlation coefficients between IMTP and ISqT, and sprint times are presented in Table 4.4. All IMTP variables reported large correlations with 0 – 5 m time in males only. In addition, PF largely correlated with the 10 – 20 m split and 0 – 30 m outcome. In relation to the ISqT, all variables largely or very largely correlated with 0 – 5 m time. Among females, IMTP or ISqT resulted in small or moderate correlations with all sprint times.

4.5.2 Stepwise Regression Analyses for Isometric Variables Predicting Sprint Performance

To investigate whether isometric strength variables could predict sprint performance, and evaluate its level of influence, a stepwise regression analysis was performed. Large correlations were observed in the 0 – 5 m split, where 0 – 5 m time was the dependent variable. IMTP IMP (0 – 200 ms) was a significant predictor of 0 – 5 m time using the formula: $0 - 5 \text{ m} = 1.309 - 0.001 * \text{IMP} (0 - 200 \text{ ms})$; $r = 0.582$, adjusted $R^2 = 0.339$, $F(1,13) = 6.666$, $p = 0.023$. ISqT RPF significantly predicted 0 – 5 m time using the formula: $0 - 5 \text{ m} = 1.291 - 0.006 * \text{RPF}$; $r = 0.606$, adjusted $R^2 = 0.367$, $F(1,13) = 7.532$, $p = 0.017$. Examining the unstandardised B coefficients with 95% CIs, results indicate that IMTP IMP (0 – 200 ms) could have a maximum effect on 0 – 5 m time between -0.22 to -0.02 seconds. ISqT RPF could have a maximum effect on 0 – 5 m time between -0.18 to -0.03 seconds. The beta coefficients for RPF and IMP 0 – 200 ms (-0.606 and -0.582 respectively) were very similar, and ISqT RPF may have a slightly greater relative influence on 0 – 5 m time (Figures 4.2 and 4.3).

Table 4.4 Inter-correlation matrix between IMTP & ISqT variables and sprint performance measures in males (top) and females (bottom)

	0 – 5 m	5 – 10 m	10 – 20 m	20 – 30 m	0 – 30 m
Males - IMTP					
PF (N)	-0.626 (-0.859 to -0.166)*	-0.039 (-0.640 to 0.561)	-0.525 (-0.882 to 0.090)*	-0.501 (-0.892 to 0.235)	-0.595 (-0.916 to 0.088)*
RPF (N/kg)	-0.527 (-0.853 to 0.020)*	-0.037 (-0.723 to 0.573)	-0.451 (-0.880 to 0.163)	-0.433 (-0.905 to 0.251)	-0.508 (-0.918 to 0.174)
Force at 100 ms (N)	-0.585 (-0.870 to -0.124)*	0.049 (-0.674 to 0.586)	-0.325 (-0.773 to 0.282)	-0.281 (-0.824 to 0.377)	-0.437 (-0.890 to 0.156)
Force at 150 ms (N)	-0.616 (-0.879 to -0.126)*	0.006 (-0.679 to 0.559)	-0.417 (-0.828 to 0.099)	-0.368 (-0.842 to 0.283)	-0.513 (-0.918 to 0.084)
Force at 200 ms (N)	-0.611 (-0.845 to -0.108)*	0.032 (-0.666 to 0.646)	-0.456 (-0.841 to 0.185)	-0.383 (-0.884 to 0.418)	-0.521 (-0.910 to 0.163)*
RFD 0–150 ms (N/s)	-0.550 (-0.823 to -0.103)*	0.018 (-0.612 to 0.548)	-0.379 (-0.684 to 0.013)	-0.300 (-0.715 to 0.246)	-0.450 (-0.769 to -0.003)
RFD 0–200 ms (N/s)	-0.556 (-0.811 to -0.089)*	0.047 (-0.511 to 0.661)	-0.436 (-0.791 to 0.063)	-0.331 (-0.769 to 0.342)	-0.471 (-0.817 to 0.086)
IMP 0–200 ms (N.s)	-0.582 (-0.879 to -0.032)*	0.082 (-0.698 to 0.629)	-0.323 (-0.729 to 0.334)	-0.297 (-0.834 to 0.389)	-0.432 (-0.893 to 0.263)

Males - ISqT

PF (N)	-0.714 (-0.939 to -0.307)**	0.392 (-0.083 to 0.791)	-0.150 (-0.576 to 0.396)	-0.121 (-0.575 to 0.472)	-0.324 (-0.741 to 0.239)
RPF (N/kg)	-0.606 (-0.918 to -0.071)*	0.419 (-0.103 to 0.832)	-0.041 (-0.540 to 0.488)	-0.012 (-0.520 to 0.510)	-0.205 (-0.759 to 0.444)
Force at 100 ms (N)	-0.547 (-0.857 to 0.021)*	0.210 (-0.214 to 0.556)	-0.120 (-0.551 to 0.477)	-0.249 (-0.596 to 0.305)	-0.310 (-0.704 to 0.233)
Force at 150 ms (N)	-0.589 (-0.867 to -0.045)*	0.245 (-0.254 to 0.627)	-0.152 (-0.607 to 0.405)	-0.249 (-0.608 to 0.320)	-0.332 (-0.749 to 0.301)
Force at 200 ms (N)	-0.541 (-0.870 to 0.057)*	0.243 (-0.274 to 0.700)	-0.156 (-0.626 to 0.409)	-0.237 (-0.621 to 0.308)	-0.308 (-0.807 to 0.337)
RFD 0–150 ms (N/s)	-0.575 (-0.860 to -0.051)*	0.107 (-0.382 to 0.555)	-0.213 (-0.589 to 0.308)	-0.255 (-0.634 to 0.216)	-0.377 (-0.767 to 0.174)
RFD 0–200 ms (N/s)	-0.521 (-0.816 to 0.061)*	0.105 (-0.426 to 0.635)	-0.223 (-0.628 to 0.324)	-0.242 (-0.650 to 0.282)	-0.353 (-0.761 to 0.247)
IMP 0–200 ms (N.s)	-0.517 (-0.517 to 0.017)*	0.239 (-0.232 to 0.607)	-0.120 (-0.575 to 0.511)	-0.261 (-0.644 to 0.315)	-0.292 (-0.775 to 0.343)

Females - IMTP

PF (N)	-0.065 (-0.707 to 0.621)	-0.394 (-0.821 to 0.352)	-0.052 (-0.788 to 0.664)	-0.255 (-0.810 to 0.540)	-0.200 (-0.815 to 0.57)
RPF (N/kg)	-0.201 (-0.803 to 0.465)	-0.432 (-0.826 to 0.273)	-0.231 (-0.891 to 0.495)	-0.406 (-0.901 to 0.468)	-0.347 (-0.877 to 0.356)

Force at 100 ms (N)	0.259 (-0.649 to 0.857)	-0.102 (-0.805 to 0.564)	0.210 (-0.529 to 0.848)	0.156 (-0.660 to 0.804)	0.161 (-0.692 to 0.788)
Force at 150 ms (N)	-0.055 (-0.682 to 0.659)	-0.331 (-0.785 to 0.311)	-0.008 (-0.717 to 0.670)	-0.137 (-0.738 to 0.552)	-0.135 (-0.714 to 0.587)
Force at 200 ms (N)	-0.134 (-0.775 to 0.532)	-0.428 (-0.854 to 0.164)	-0.051 (-0.743 to 0.673)	-0.246 (-0.823 to 0.444)	0.225 (-0.758 to 0.387)
RFD 0–150 ms (N/s)	0.016 (-0.685 to 0.652)	-0.275 (-0.813 to 0.353)	0.013 (-0.764 to 0.707)	-0.079 (-0.738 to 0.597)	-0.078 (-0.760 to 0.671)
RFD 0–200 ms (N/s)	-0.061 (-0.678 to 0.625)	-0.373 (-0.823 to 0.293)	-0.029 (-0.795 to 0.657)	-0.187 (-0.803 to 0.531)	-0.167 (-0.764 to 0.459)
IMP 0–200 ms (N.s)	0.172 (-0.677 to 0.776)	-0.169 (-0.800 to 0.525)	0.166 (-0.622 to 0.774)	0.056 (-0.645 to 0.727)	0.078 (-0.647 to 0.704)
Females - ISqT					
PF (N)	-0.250 (-0.018 to 0.297)	-0.439 (-0.782 to 0.396)	-0.363 (-0.838 to 0.354)	-0.439 (-0.903 to 0.439)	-0.413 (-0.869 to 0.277)
RPF (N/kg)	-0.410 (-0.889 to 0.09)	-0.464 (-0.845 to 0.339)	-0.594 (-0.914 to 0.095)	-0.614 (-0.908 to 0.063)	-0.587 (-0.916 to -0.128)
Force at 100 ms (N)	-0.242 (-0.768 to 0.502)	-0.416 (-0.843 to 0.244)	-0.125 (-0.786 to 0.508)	-0.287 (-0.823 to 0.495)	-0.289 (-0.783 to 0.384)
Force at 150 ms (N)	-0.177 (-0.736 to 0.574)	-0.392 (-0.815 to 0.417)	-0.159 (-0.837 to 0.641)	-0.280 (-0.883 to 0.571)	-0.272 (-0.806 to 0.468)

Force at 200 ms (N)	-0.144 (-0.747 to 0.648)	-0.374 (-0.851 to 0.549)	-0.180 (-0.802 to 0.654)	-0.280 (-0.859 to 0.662)	-0.265 (-0.808 to 0.660)
RFD 0–150 ms (N/s)	0.119 (-0.733 to 0.735)	-0.216 (-0.814 to 0.506)	-0.135 (-0.727 to 0.742)	-0.102 (-0.787 to 0.697)	-0.050 (-0.766 to 0.670)
RFD 0–200 ms (N/s)	0.138 (-0.614 to 0.780)	-0.210 (-0.841 to 0.612)	-0.055 (-0.748 to 0.770)	-0.121 (-0.853 to 0.792)	-0.062 (-0.807 to 0.742)
IMP 0–200 ms (N.s)	-0.241 (-0.742 to 0.495)	-0.418 (-0.831 to 0.271)	-0.166 (-0.839 to 0.487)	-0.311 (-0.836 to 0.510)	-0.308 (-0.827 to 0.408)

IMP = impulse; IMTP = isometric mid-thigh pull; ISqT = isometric squat; PF = peak force; RFD = rate of force development; RPF = relative peak force.

Results are presented as r (95% CI). Statistically significant correlations are presented in bold. * $p \leq 0.05$

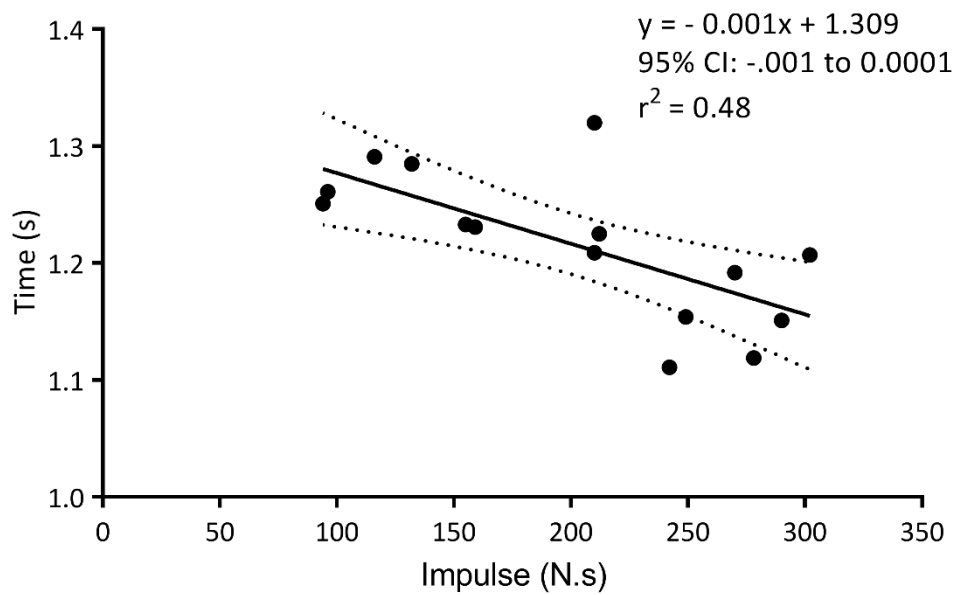


Figure 4.2 - Scatter plot correlative findings between IMTP IMP 0 – 200 ms (N.s) and 0 – 5 m time among male sprinters.

Note: Dashed line demonstrates 95% CI (1.205 – 1.413)

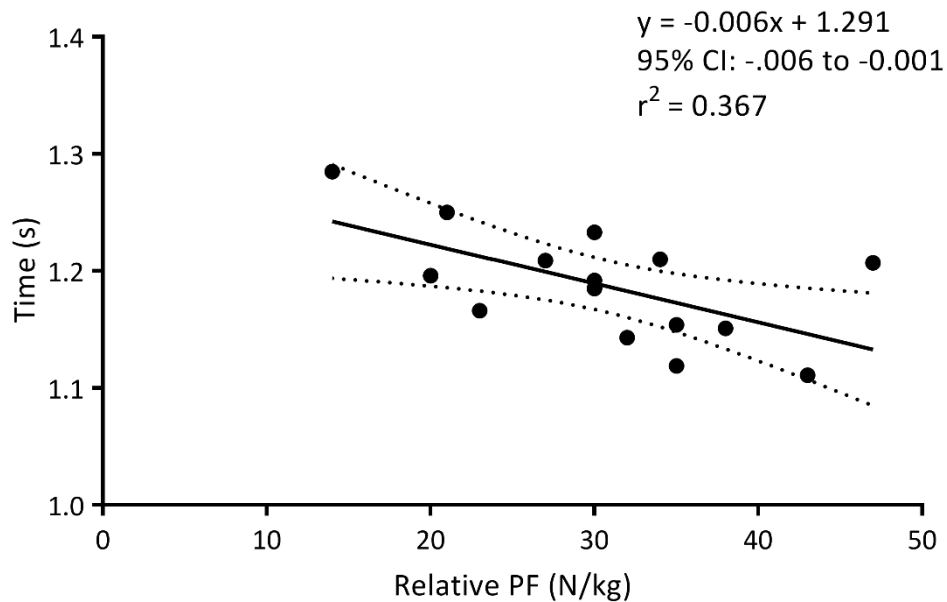


Figure 4.3 - Scatter plot correlative findings between ISqT RPF (N/kg) and 0 – 5 m time among male sprinters.

Note: Dashed line demonstrates 95% CI (1.206 – 1.375)

4.6 Discussion

It was hypothesised that IMTP and ISqT variables would relate to 0 – 5 m sprint performance, we can accept this hypothesis only for the male populations and reject it for the female population. The present study supports the findings of Tillin *et al.* (2013), Wang *et al.* (2016) and Thomas *et al.* (2015a) who reported that measures of isometric strength negatively correlated with 0 – 5 m sprint performance in male rugby players and is the first study to detail this relationship among a group of highly trained sprint athletes. While Conlon *et al.* (2013) and Townsend *et al.* (2017) also reported this relationship with female athletes, the males and females were analysed together and this is a problem as sex differences exist in strength (Fuster *et al.* 1998). Within the study by Conlon *et al.* (2013) the athletes were from various sports, therefore it is unknown whether this relationship exists within the female population. In contrast to the present study, moderate or large correlations have been reported between IMTP variables and 10 m (West *et al.* 2011, Conlon *et al.* 2013), 20 m (Conlon *et al.* 2013, Tillin *et al.* 2013, Thomas *et al.* 2015a) and performances ≥ 30 m (Conlon *et al.* 2013, Wang *et al.* 2016) among athletes from field-based sports. This study supports the findings of Healy *et al.* (2018), reporting that IMTP measures of maximum strength result in small or moderate correlations with any of the sprint times ≥ 10 m, in both male and female sprint athletes. Healy *et al.* (2018) reported similar PF and RPF values as this study for both sexes.

Amongst males, the 0 – 5 m split largely correlated to the outcome of 0 – 30 m time ($r = -0.719$, $p = 0.003$). This details the 0 – 5 m segment is an important contributor to the acceleration phase and that it may exert a large influence on acceleration up to 30 m. While other sections displayed stronger correlations with each other, such as 10 – 20 m and 20 – 30 m ($r = 0.914$, $p < 0.05$), the fact 0 – 5 m largely correlated with the outcome of 0 – 30 m displays this phase does differ to the other phases but it very important in terms of the outcome. Males reported large negative correlations between PF, RFD and IMP measures in the IMTP and ISqT and 0 – 5 m sprint time. Further, IMTP PF largely correlated with the 10 – 20 m time ($r = -0.525$, $p < 0.05$). This suggests that higher levels of maximum strength and its derivatives may result

in lower initial sprint times, and higher levels of maximal strength may result in lower sprint times through the 10 – 20 m section of the race. Since the 0 – 5 m split very largely correlates to the overall 0 – 30 m sprint performance, this may be an important quality for male sprinters to possess. However, this is not supported by the results of the female group, which may be due to the differences that exist in strength with the male sprinters displaying significantly higher levels in absolute maximum strength compared to the females in the IMTP. Interestingly, there was no significant difference between male and female sprinters in any of the ISqT force measures. Brady *et al.* (2018b) reported that female athletes produced an additional 28.5% RPF during an ISqT compared with the IMTP. The authors explained that this may be due to the elimination of the use of the upper extremity force during the ISqT compared with the IMTP. Female athletes have been reported as weaker in the upper extremity compared to their male counterparts (Yanovich *et al.* 2008), and this may explain why significant differences were reported between genders in the IMTP but not in the ISqT in this study. In addition, the female athletes may have utilised an inefficient technique compared to the male athletes. Further research is required to determine why this difference exists between genders. In addition, future research should examine these relationships among the female population with a larger sample, as the sample size in this study may be a limitation of the study. S&C coaches need to consider whether the IMTP & ISqT are the most appropriate test for female sprinters to perform. With no relationships observed with sprint acceleration performance, these tests may not be the most appropriate. However, the female participants in this study would be considered weak (IMTP RPF = 21.9 N/kg; excludes body mass), when compared to female volleyball players (IMTP RPF = 68.6 N/kg; includes body mass) (Haff *et al.* 2015). S&C coaches should consider improving the female sprinters strength levels, and identifying whether increases in strength levels are associated with improvements in performance.

While all reliable variables measured in the IMTP and ISqT largely or very largely correlated with 0 – 5 m sprint time among the male participants, IMTP IMP 0 – 200 ms (N.s) significantly predicted 0 – 5 m time accounting for 33.9% of the variance in 0 – 5 m performance. By comparison, ISqT RPF

significantly predicted 0 – 5 m time accounting for 36.7% variance in 0 – 5 m performance. Therefore, when selecting variables to analyse from these tests, coaches should include IMTP IMP 0 – 200 ms and ISqT RPF for males. However, 63 – 66 % of the variance was not accounted for by isometric testing, future research should aim to determine what aspects of performance account for this variance as it is a large portion of the performance. When examining the 95% CIs of the unstandardised B coefficients the data indicates that isometric strength may have a sizable influence on 0 – 5 m time but the lower bound 95% CI indicates that this influence could also be very small. In addition, it should be noted that the authors do not recommend that practitioners use isometric tests instead of sprint tests to analyse sprint performance. Our results indicate that in a group of well-trained male sprinters, isometric measures of strength correlate with performance in the first 5 m of the sprint and this is important for coaches and practitioners monitoring specific types of strength that relate to initial acceleration ability.

4.7 Practical Applications

The present study demonstrated that variables measured in the IMTP and ISqT are correlated with 0 – 5 m sprint performance in male sprinters. Practitioners and researchers are advised to use split times including the 0 – 5 m split along with an outcome measure when investigating correlations because sprinting is a skill requiring a high technical and physical demands and these change throughout the sprint phases. Whilst it is unknown if increases in isometric strength measures will transfer to improvements in speed time, results from this study detail that isometric strength measures account for 33 – 37% of the variance in 0 – 5 m performance. More research is needed to determine the reasons behind this relationship differing among females. S&C coaches should consider whether the IMTP & ISqT are the appropriate tests to select for female sprinters. Improving the basic strength levels of female sprinters should be considered as a training intervention.

4.8 Conclusions

Results suggest that PF, force at 100, 150 and 200 ms, RFD (0 – 150 and 0 – 200 ms) and IMP (0 – 200 ms) measured during the IMTP and ISqT largely correlate to 0 – 5 m sprint performance in male athletes. Isometric strength can have a sizable influence on 0 – 5 m time, but in some cases, the maximum effect could be very small.

Chapter 5: Study 4 – The Relationship between the Isometric Mid-Thigh Pull and Sprint Acceleration Kinematics in Male Sprinters

Brady, C.J., Harrison, A.J., Flanagan, E.F., Haff, G.G., Comyns, T.M. 2019.
The relationship between isometric strength and sprint acceleration in
sprinters. *The Journal of Strength and Conditioning Research*. (Under
Review)

5.1 Preface

Study 3 identified that IMTP and ISqT measures correlated with 0 – 5 m sprint performance from the blocks among male sprinters. When building its new facility, SII had also installed 30 m of Optojump technology (Microgate, Bolzano, Italy). Since running speed is a product of stride length and stride frequency, and isometric strength was reported to relate to 0 – 5 m time, further analysis was carried out to examine if isometric strength related to sprint kinematics from the blocks measured through the Optojump system. The large correlations between isometric strength and 0 – 5 m sprint performance were observed among the male sprinters, therefore, only the male sprint data was analysed for this study. Having observed relationships between the IMTP and ISqT and sprint performance, only one isometric test was analysed for this study due to the large amount of variables to examine (isometric variables and sprint kinematic variables). The IMTP was chosen, as currently it is the most popular isometric test and many of the sprinters in the study performed weightlifting exercises in their training, therefore the IMTP matched their training backgrounds. This paper provides practical applications for coaches and practitioners.

5.2 Abstract

The majority of biomechanical research of the sprint start has focused on reporting kinematic and kinetic factors without any additional measures of physical ability. The primary aim of this study was to determine whether isometric strength qualities were related to sprinting kinematics over the first 5 m of a sprint initiated from the starting blocks. Fifteen male sprinters familiarised with the IMTP participated in this study. Athletes performed 3 maximal effort IMTPs with PF, RPF, IMP, RFD and time specific force measured, followed by 3 by 30 m sprints from blocks through Optojump and timing gates, measuring step length, contact time, flight time and velocity. Correlation analyses were used to assess the relationships between measures (alpha $p \leq 0.05$). Large correlations were reported between IMTP variables and the velocity of step 2 ($r \geq 0.544$, $p < 0.05$). Force at 100 ms largely correlated with modified rear block clearance velocity ($r = 0.556$, $p < 0.05$).

Rear block clearance relative step length largely correlated with IMP 0 – 200 ms and force at 100 ms ($r = 0.547$ and $r = 0.647$ respectively, $p < 0.05$). Flight time and contact time displayed small correlations with IMTP variables. Higher force generation in the IMTP was associated with faster velocities and longer rear block clearance relative step length. The IMTP may be an off-track test that is appropriate for use in profiling sprint acceleration capacity.

5.3 Introduction

The sprint start is a fundamental component of all track and field sprint events (≤ 400 m). At the start of all of these events, athletes must commence from starting blocks, where they need to produce maximum acceleration from zero velocity. Sprint start performance is strongly correlated with overall 100 m time (Mero 1988, Bezodis *et al.* 2015) and therefore is a very important component of the race. The “sprint start” is rarely clearly defined, the majority of studies have usually focused on the block phase and/or one or more of the subsequent steps. The sprint start is often a self-selected “set” position; where the sprinter chooses the location and inclination of the two foot plates in the blocks. While there appears to be no universal optimum body configuration in the “set” position, a medium block spacing, which enables hip extension and a considerable rear leg force contribution is encouraged (Bezodis *et al.* 2019).

Various biomechanical models of sprinting and the sprint start performance have been presented in the literature. The “deterministic model” of Hay and Reid (1982) details the factors that affect performance of sprinting and the relationships between those factors using simple mathematical relationships. For example, running speed is expressed as the product of step length and step frequency and the deterministic model divides these factors into subcomponents such as flight distance, flight time and take-off distance. The model identifies biomechanical factors that limit sprint performance, however a drawback of this method is that many of the factors derived may not be readily observable in field situations. More recently, there are optical measuring systems on the market to measure step kinematics such as step length, contact time, flight time and step frequency directly and provide

feedback immediately after a run, and are more readily available in field settings. Graham and Harrison (2006) have provided a deterministic model for the sprint start and the first 5 m of the race (adapted in Figure 5.1), and many of these biomechanical factors can be derived from the optical measuring systems. Factors shaded in grey in Figure 5.1 can be obtained directly or calculated from the output, or a modified version can be acquired (modified rear block clearance time, modified rear block clearance velocity). While this leaves some factors unmeasured, it provides coaches and practitioners with a starting point, and ability to focus on the key components, which will help to drive performance.

The majority of research on the sprint start has focused on the centre of mass at block exit (where both the front and rear foot have cleared contact with the block face). This is determined by the IMP produced in the push phase, where athletes can either produce greater force, or maximise force production within certain time limits. Bezodis *et al.* (2019) reviewed the biomechanics of the sprint start but failed to consider the underlying strength characteristics. The majority of biomechanical research typically focuses on reporting kinematic and kinetic factors, without any additional measures of physical ability. Factors such as neuromuscular function, morphological features (Kubo *et al.* 2011) and anthropometry (Weyand and Davis 2005) affect sprint performance. For example, the tendon structures of highly trained sprint athletes are more compliant than those of untrained participants for the knee extensors and a thicker medial side knee extensor is associated with superior 100 m sprint performance (Kubo *et al.* 2011). Further, Weyand and Davis (2005) compared body mass and stature values for the world's fastest performers at track racing from 100 m to 10,000 m and observed that as running distance decreased, the body mass index (BMI) of the athlete increased, which would allow sprinters to achieve greater support force compared to middle and long distance athletes. Force and power production of the lower extremities are critical factors for superior sprint performance (Mero *et al.* 1981). General and specific measures of physical ability, such as force and power production have been reported to positively correlate to the push phase (exiting the blocks) (Maulder *et al.* 2006, Smirniotou *et al.* 2008) and also early acceleration (Sleivert and Taingahue 2004, Nagahara *et al.*

2014, Brady *et al.* 2019). Slawinski *et al.* (2010) established that sprinters with greater “explosive strength” are able to generate a greater RFD and IMP, and therefore a greater velocity from the blocks to the toe-off of the second step.

There is a need for an applied, practical test that allows for the measurement of physical abilities such as maximum force production and RFD. The IMTP is a common test used to measure an athlete’s maximum strength capabilities, in addition to RFD and IMP. Recently, Brady *et al.* (2019), reported that amongst male sprint athletes, strength characteristic measurements (force, IMP, RFD) derived from the IMTP, largely correlated with 0 – 5 m time ($r = -0.527$ to -0.626 , $p < 0.05$). These indicating higher levels of maximum strength and the ability to express this rapidly may result in a lower initial sprint time, and therefore should be considered an important quality for sprinters to possess. Based upon this interpretation of the results it is clear that strength is a vital component of sprint start performance, and after the initial start phase (0 – 5 m), the physical demands change and other factors become more important.

It is unknown whether a relationship exists between physical strength, measured during a maximal isometric test and sprinting kinematics. Previous research has suggested that stride length is a key factor in acceleration performance. Aerenhouts *et al.* (2012) detailed that adult senior sprinters had significantly longer first step lengths and achieved higher velocities at 5 m than junior athletes. There was no significant difference in height between the male junior and senior athletes, but the seniors were heavier, had a larger limb circumference and a higher skeletal muscle mass than the juniors. Notably, younger athletes are unable to produce as much knee joint power during the stance phase and this may contribute to the shorter step lengths (Debaere *et al.* 2017). Aerenhouts *et al.* (2012) concluded that athletes with a higher force potential, with greater muscularity can only result in a better performance when this force can be applied at the optimal moment and direction. Performance in each step of the sprint is affected by the preceding steps, and analysing only the mean of events over a specific phase of the event may not be sensitive enough to determine relationships. Nagahara *et al.* (2014) examined the demand of strength-power capabilities represented by

traditional and ankle specific vertical jump modalities relative to sprint acceleration ability during the entire acceleration phase. Correlation coefficients among vertical jump performances and between those and the 60 m sprint time and sprint acceleration at each step were calculated. Results displayed that acceleration was moderately or largely correlated with SJ height from the 6th to the 10th steps ($r = 0.48 - 0.54$) and with CMJ height from the 5th to the 11th steps ($r = 0.46 - 0.54$). The authors did not measure any step kinematics and Maćkała *et al.* (2015) noted that future research should consider the analysis of speed kinematics changes on a step-to-step basis, similar to the study by Nagahara *et al.* (2014).

Previous research demonstrated large relationships between strength characteristics measured during the IMTP and 0 – 5 m sprint performance from the blocks (Brady *et al.* 2019). It is unknown whether there is any relationship between isometric strength and sprinting kinematics. Therefore, the aim of this study was to determine whether isometric strength qualities related to sprint performance had any meaningful relationship with sprinting kinematics from the blocks and over the first 5 m. It was hypothesised that IMTP variables would relate to stride length and velocity in step kinematics over the first three steps.

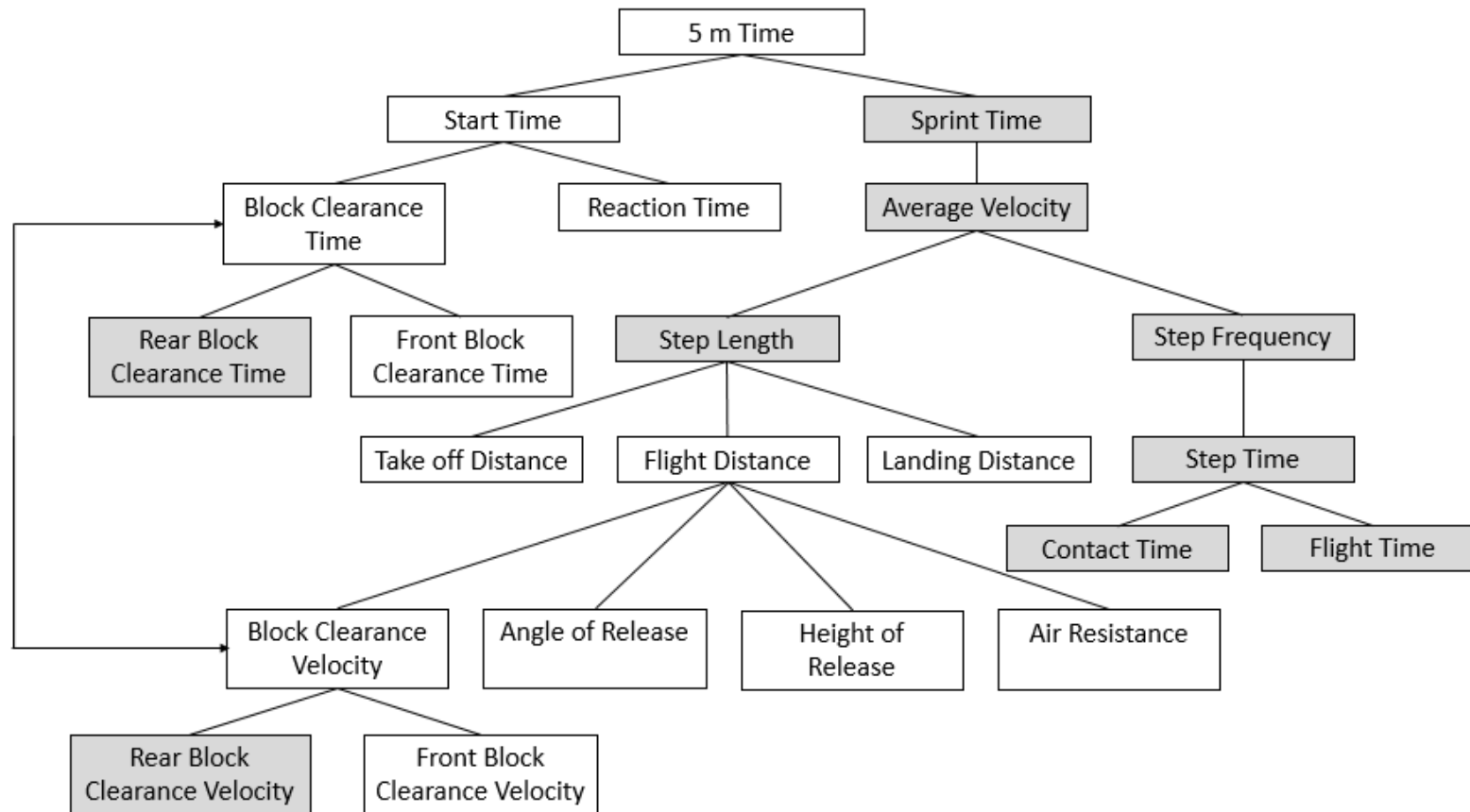


Figure 5.1 - Deterministic model of the sprint start (adapted from Graham and Harrison, 1996).

Note: Factors shaded in grey can be obtained directly or calculated from the Optojump (Microgate, Bolzano, Italy) output, or a modified version can be attained

5.4 Methods

5.4.1 Experimental Approach to the Problem

A cross-sectional study design was undertaken to assess the relationship between the IMTP and sprint kinematics. All athletes took part in a familiarisation session for the IMTP one week prior to the testing session. On the day of testing, athletes completed a general warm up, an isometric specific warm up, maximal effort IMTPs followed by an individualised sprint warm up and 3 by 30 m sprints from blocks.

5.4.2 Participants

Fifteen male sprinters (mean \pm SD, age: 22 ± 4 years; age range: 18-29; body height: 1.81 ± 0.05 m; body mass: 75.9 ± 5.8 kg) agreed to participate in this investigation. There were nine 100 m sprinters (pb = 10.92 ± 0.22 s), four 110 mH (pb = 14.1 ± 0.23 s) and two 400 m sprinters (pb = 48.43 ± 0.14 s). Six of the athletes competed regularly at an international level, whereas the remaining nine competed regularly at a national level. All had at least 2 years of sprint and strength training experience. The athletes' regular training programme consisted of 3-4 sprint training sessions and 2-3 strength training sessions. Ethical approval was provided by the University's Research Ethics Review Board. Additionally, athletes were informed of the benefits of the investigation and written consent forms were completed before testing in compliance with the Declaration of Helsinki.

5.4.3 Procedures

5.4.3.1 Isometric Strength Testing

Athletes took part in a familiarisation session for the IMTP after an explanation of the study and signing of the informed consent (Brady *et al.* 2018b). One week later, athletes completed the testing session following a 48-hour rest. Athletes completed a general warm-up consisting of 3 minutes of cycling, 10 bodyweight squats, 10 bodyweight walking lunges and 10 gluteal bridge exercises. They then completed the isometric specific warm-up as previously reported in the literature (Brady *et al.* 2018b), consisting of

pulling the bar for 5 seconds at a self-directed 50%, 3 seconds at 70% to 80% and 3 seconds at 90% of maximal effort with 1-minute recovery between efforts. Athletes then rested for 2 minutes before completing their maximum efforts.

Athletes were set in the correct position, replicating the body position at the beginning of the second pull position of the clean or snatch (adopting sagittal knee angles of $140^{\circ} \pm 4^{\circ}$ and hip angles $139^{\circ} \pm 2^{\circ}$) (Guppy *et al.* 2019). This position is the strongest and most powerful position during weightlifting movements, generating the highest forces and velocities of any part of the lift (Garhammer 1993) and has been reported to relate to both jumping (Haff *et al.* 2005, Kawamori *et al.* 2006) and sprinting performances (Thomas *et al.* 2015a, Brady *et al.* 2019). Feet were placed between hip- and shoulder-width apart with the toes pointed slightly outward. Angles were measured using a hand-held goniometer; grip and foot width were measured and remained consistent between trials. Athletes used lifting straps to ensure grip strength was maintained (Brady *et al.* 2018b). Athletes were required to maintain their position throughout the test. Athletes completed 3 maximal efforts with each effort lasting 5 seconds with a 2-minute rest between trials. For each trial, athletes were instructed to “pull as hard and as fast as you can” to ensure maximal force was achieved. Athletes were instructed to get ready, and then were given a countdown of “3, 2, 1, pull!”. Verbal encouragement was provided during each trial. Athletes completed a fourth trial if they lost their position, grip or the effort was not deemed a maximum effort, or if there was a greater than 250 N difference between efforts (Kraska *et al.* 2009).

All isometric testing was conducted on a custom-made isometric rack (Sorinex inc., Lexington, SC), allowing the placement of the bar at 0.5 cm intervals and permitting the desired position for each athlete. The rack was anchored to the floor and placed over a Kistler 9287 CA force platform (Winterthur, Switzerland), sampling at 1000 Hz. The collection period for each trial was set at 12 seconds, and a baseline was measured during the 3-second countdown prior to the initiation of the pull (Brady *et al.* 2018b). The criterion onset threshold and onset of the contraction were defined as the point where the force exceeded 5 SD from baseline (Dos’Santos *et al.* 2017a). PF was reported as maximum force generated during the 5 second trial minus

the athlete's body weight. PF was also reported relative to body mass (N/kg). Since contact times during sprinting range from ~ 100 – 200 ms (Mero *et al.* 1992), these limits were used when selecting isometric variables of time specific force epochs, RFD and IMP. Force at 100, 150 and 200 ms from the initiation of the pull was therefore determined to align with the contact times in sprinting. RFD was calculated ($\Delta\text{Force}/\Delta\text{Time}$) and was applied to specific time bands (0 – 100, 0 – 150 and 0 – 200 ms) previously reported in the literature (Haff *et al.* 2015). IMP was determined as average force divided by the change in time over 100 and 200 ms.

5.4.3.2 30 m Sprint Testing

After the isometric strength testing, athletes rested for ten minutes before completing an individualised race-specific warm up, lasting ~30 minutes, including 2 by 10 m starts from blocks. Athletes completed 3 maximal effort 30 m sprints from a block start with a minimum of six minutes' recovery between sprints through Optojump (Microgate, Bolzano, Italy) and dual-beam timing gates (Microgate, Bolzano, Italy) positioned at 5 and 30 m. Split times from 0 – 5 m and 0 – 30 m were recorded. Optojump is an optical measuring unit consisting of 2 parallel bars containing LEDs, and any interruptions between the bars is detected and calculates the duration to obtain kinematic variables such as step length, contact time, flight time and step frequency (Healy *et al.* 2016b). Timing was initiated at the instant the athletes hand left the track surface (start-pad) using a previously validated protocol that synchronised timing gates to the Optojump system (Healy *et al.* 2016b). Healy *et al.* (2016a) reported high validity in step parameters during running (ICC = 0.96-0.99; mean bias = 0.4 – 2.7%). A schematic representation of the set up and definition of the events and associated phases during the sprint start, described using the terminology applied consistently in this investigation are detailed in Figure 5.2 and Table 5.1. Step length was reported as relative step length; this was calculated as the athlete's step length divided by the leg length. Leg length was estimated as 0.53 times the athletes height (Contini 1972).

Table 5.1 Definition of the events and associated phases during the sprint start

Terminology	Description
Time to 5 meters	From when the athletes hand left the start-pad to the 5 m timing gate
Modified rear block clearance velocity	The “rear block step length” divided by “modified rear block clearance time”
Velocity step 1	The distance between the 1 st and 2 nd contacts divided by the time between these two events
Velocity step 2	The distance between the 2 nd and 3 rd contacts divided by the time between these two events
Velocity step 3	The distance between the 3 rd and 4 th contacts divided by the time between these two events
Rear block step length	The length of the step from the foot leaving the rear block to first stance touchdown
Step length step 1	The length of the step from the first contact to the second contact
Step length step 2	The length of the step from the second contact to the third
Step length step 3	The length of the step from the third contact to the fourth
Modified rear block clearance time	Time taken from hand leaving the start-pad to the rear foot making the first stance touchdown
Flight time step 1	Time from toe off of the first foot contact to touchdown of the second contact
Flight time step 2	Time from toe off of the second contact to touchdown of the third contact

Flight time step 3	Time from toe off of the third contact to touchdown of the fourth contact
First contact time	The contact time of the first stance touchdown after leaving the rear block
Second contact time	The contact time of the second stance touchdown after leaving the front block
Third contact time	The contact time of the third stance touchdown
Fourth contact time	The contact time of the fourth stance touchdown

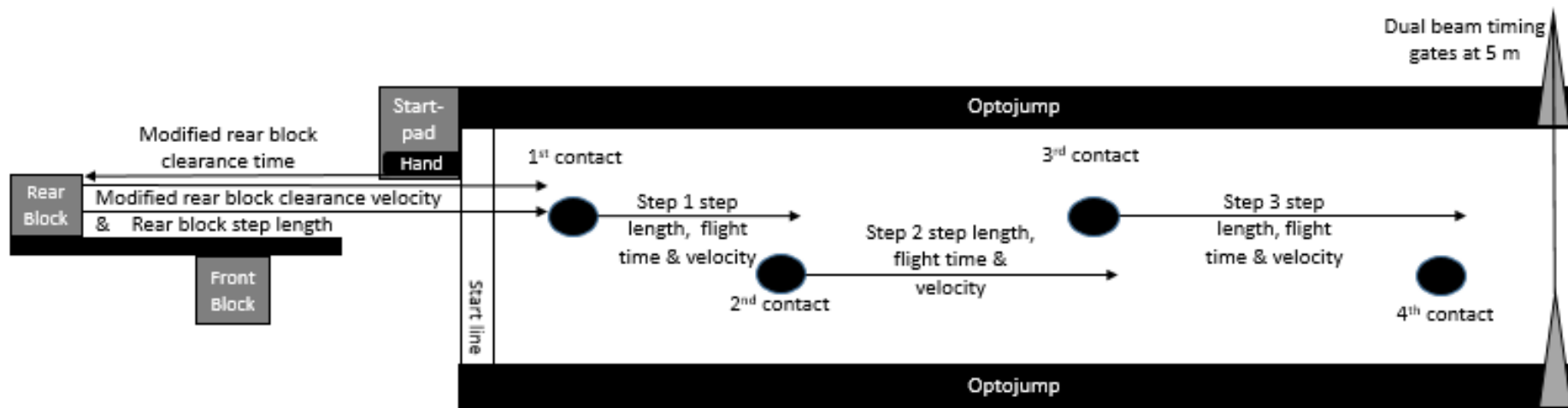


Figure 5.2 - Schematic representation of the testing set up and the events and associated phases during the sprint start

5.4.4 Statistical Analyses

All force-time data were analysed using a custom spreadsheet to determine specific force–time characteristics. Normality was assessed for all variables using the Shapiro-Wilk statistic. All variables were normally distributed ($p > 0.05$). Relationships between IMTP variables and sprint times were determined by Pearson product-moment correlations ($\alpha \leq 0.05$) using SPSS software (version 22.0, IBM Corp, Armonk, NY). The best repetitions based on PF and 30 m sprint times were used for analysis (Beattie *et al.* 2017b). Correlations were evaluated as: small (0.1–0.29), moderate (0.3–0.49), large (0.5–0.69), very large (0.7–0.89), nearly perfect (0.9–1.0), and perfect (1.0) (Hopkins *et al.* 2009). Reliability for isometric variables and sprint times were calculated by determining the CV, calculated as the TE and expressed as a CV%, the ICC and 95% CIs using a Microsoft Excel spreadsheet (Hopkins 2015). Acceptable reliability was determined at an ICC ≥ 0.8 and a CV $\leq 10\%$ (Hopkins 2000). Based on the 95% CI of the ICC estimate, values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.90 are indicative of poor, moderate, good, and excellent reliability, respectively (Koo and Li 2016).

5.5 Results

The results of the reliability analysis of the IMTP measures and sprint times are presented in Table 5.2, along with the descriptive statistics (mean \pm SD). All measures displayed acceptable reliability with ICCs above 0.83 and CVs below 9.9% except for IMP (0 – 100 ms) and RFD (0 – 100 ms), which were deemed unreliable and excluded from further analysis. IMTP PF and RPF displayed ‘excellent’ reliability with the lower bound 95% CI > 0.9 (Koo and Li 2016). Force at 150 ms, 200 ms and IMP 0 – 200 ms displayed ‘good’ reliability with the lower bound 95% CI ≥ 0.79 and Force at 100 ms, RFD 0 – 150 ms and 0 – 200 ms displaying ‘moderate’ reliability with the lower bound CI ≥ 0.57 (Koo and Li 2016). Descriptive statistics (mean \pm SD) for kinematic variables measured from the Optojump are detailed in Table 5.3.

Table 5.2 Descriptive statistics and within session reliability variables attaining a criteria of an ICC > 0.8 and a CV < 10% with 95% confidence intervals

	Mean ± SD	ICC	CV%
IMTP PF (N)	2070 ± 548	0.97 (0.92 – 0.99)	5.6 (4.1 – 9.0)
IMTP RPF (N/kg)	27.3 ± 7.2	0.97 (0.92 – 0.99)	5.6 (4.1 – 9.0)
IMTP Force at 100 ms (N)	1186 ± 292	0.85 (0.62- 0.95)	9.9 (7.3 – 15.4)
IMTP Force at 150 ms (N)	1463 ± 312	0.93 (0.79 – 0.97)	6.5 (4.7 – 10.5)
IMTP Force at 200 ms (N)	1612 ± 365	0.94 (0.83 – 0.98)	6.3 (4.6 – 10.1)
IMTP RFD 0 – 150 ms (N/s)	7527 ± 1594	0.83 (0.57 – 0.94)	9.8 (7.1 – 15.9)
IMTP RFD 0 – 200 ms (N/s)	6392 ± 1459	0.86 (0.64 – 0.95)	8.4 (6.1 – 13.6)
IMTP IMP 0 – 200 ms (N.s)	220 ± 51	0.93 (0.8 – 0.98)	6.9 (5.0 – 11.1)
0 – 5 m (s)	1.187 ± 0.048	0.83 (0.56 – 0.94)	1.7 (1.3 – 2.7)
0 – 30 m (s)	4.133 ± 0.102	0.97 (0.93 – 0.99)	0.4 (0.3 – 0.7)

IMTP = isometric mid-thigh pull; RFD = rate of force development; IMP = impulse; RPF = relative peak force. Results are presented as ICC/CV (95% CI)

Table 5.3 Descriptive statistics of the kinematic variables from the Optojump

Variable	Mean \pm SD
Modified rear block clearance velocity	4.07 \pm 0.54 m/s
Velocity step 1	4.44 \pm 0.39 m/s
Velocity step 2	5.5 \pm 0.47 m/s
Velocity step 3	5.7 \pm 0.33 m/s
Rear block relative step length	1.46 \pm 0.14
Relative step length step 1	1.10 \pm 0.89
Relative step length step 2	1.30 \pm 0.15
Relative step length step 3	1.40 \pm 0.11
Modified rear block clearance time	0.346 \pm 0.333 s
Flight time step 1	0.051 \pm 0.017 s
Flight time step 2	0.057 \pm 0.011 s
Flight time step 3	0.076 \pm 0.013 s
First contact time	0.187 \pm 0.018 s
Second contact time	0.169 \pm 0.016 s
Third contact time	0.159 \pm 0.012 s
Fourth contact time	0.140 \pm 0.009 s

Pearson correlation coefficients between the sprint kinematics and IMTP variables and 0 – 5 m are presented in Table 5.4 and Figure 5.3. Modified first step velocity was very largely correlated with 0 – 5 m time ($r = -0.755$, $p = 0.001$). Velocity of step 2, step 3 and modified rear block clearance time were largely correlated with 0 – 5 m time ($r = -0.532$, $p = 0.041$; $r = -0.522$, $p = 0.046$; $r = 0.593$, $p = 0.02$ respectively). All IMTP variables largely correlated with 0 – 5 m time ($r = -0.527$ to -0.626 , $p < 0.05$). All other kinematic variables resulted in small or moderate correlations with 0 – 5 m time.

Force at 100 ms was largely correlated with modified rear block clearance velocity ($r = 0.556$, $p = 0.031$). All other IMTP variables were moderately correlated with modified rear block clearance velocity ($r \leq 0.469$, $p > 0.05$). IMTP variables and velocity of step 1 were small correlations ($r \leq 0.014$, $p > 0.05$). IMTP variables were largely (IMP 0 – 200 ms) or very largely (all other variables) correlated with velocity of step 2 ($r \geq 0.675$, $p < 0.05$). IMTP variables and velocity of step 3 were small or moderate correlations ($r \leq 0.396$, $p > 0.05$).

IMP (0 – 200 ms) and force at 100 ms were largely correlated with rear block relative step length ($r = 0.547$, $p = 0.035$ and $r = 0.647$, $p = 0.009$) respectively. All other IMTP variables and rear block relative step length were small or moderate correlations ($r \leq 0.487$, $p > 0.05$). IMTP variables displayed small or moderate correlations with relative step length of step 1 ($r \leq 0.356$, $p > 0.05$). Force at 100 ms was largely correlated to relative step length of step 2 ($r = 0.543$, $p = 0.036$), all other IMTP variables were small or moderate correlations ($r \leq 0.441$, $p > 0.05$). Force at 100 ms was largely correlated to relative step length of step 3 ($r = 0.533$, $p = 0.041$), all other IMTP variables were small or moderate correlations ($r \leq 0.436$, $p > 0.05$).

All correlations between IMTP variables and time to first touchdown, flight times and contact times were small correlations ($r \leq 0.403$, $p > 0.05$).

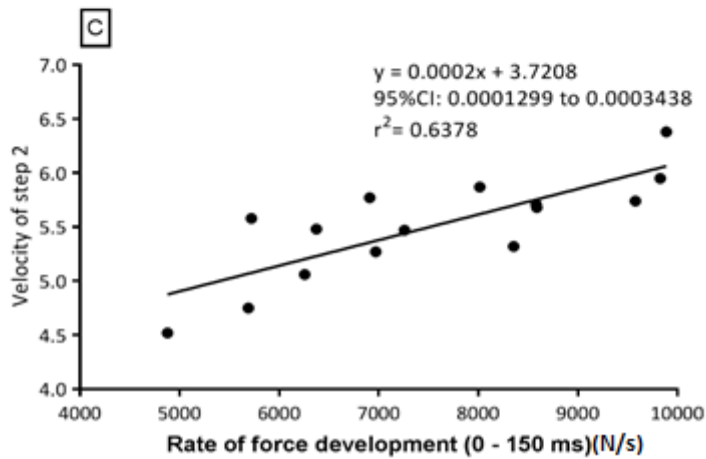
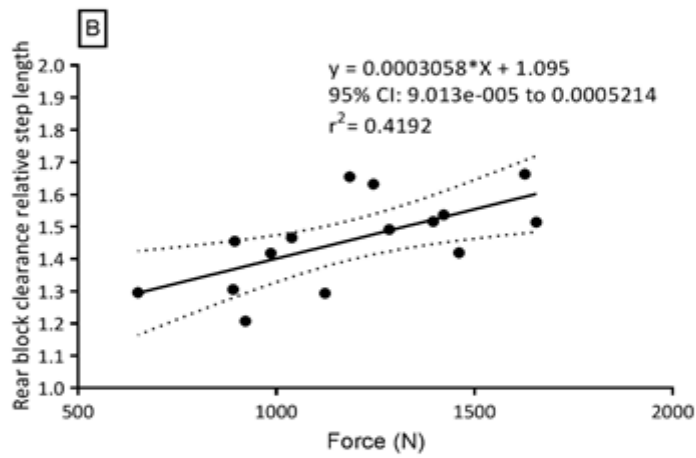
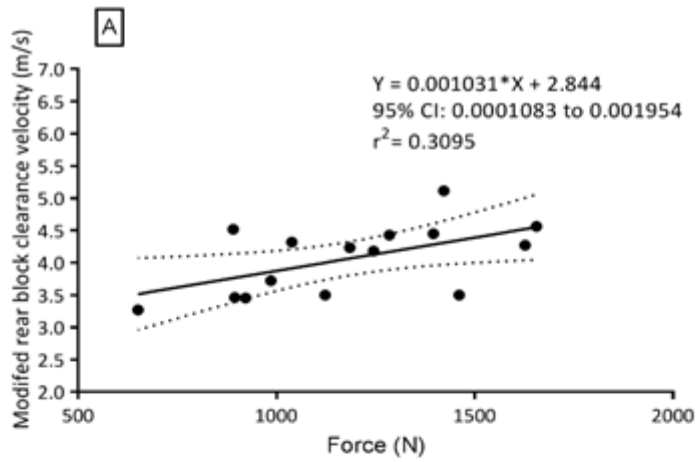


Figure 5.3 - Scatterplot correlative findings with 95% CIs between (A) IMTP force at 100 ms and modified rear block clearance velocity, (B) IMTP force at 100 ms and rear block clearance relative step length and (C) IMTP RFD (0 – 150 ms) and velocity of step 2.

Note: Dashed line represents 95% CIs. CI indicates confidence interval

Table 5.4 Inter-correlation matrix between IMTP variables, sprint kinematic variables and 0 – 5 m time

	Peak Force (N)	Relative Peak Force (N/kg)	RFD 0-150ms (N/s)	RFD 0-200ms (N/s)	Impulse 0-200ms (N.s)	Force 100 ms (N)	Force 150ms (N)	Force 200ms (N)	0 - 5 m (s)
0 – 5 m time	-0.626* (-0.859, - 0.166)	-0.527* (-0.853, 0.020)	0.550* (-0.823, - 0.103)	-0.556* (-0.811, 0.089)	-0.582* (-0.879, - 0.032)	-0.585* (-0.870, - 0.124)	-0.616* (-0.879, - 0.126)	-0.611* (-0.845, - 0.108)	1*
Modified rear block clearance velocity	0.434 (-0.117, 0.780)	0.34 (-0.229, 0.746)	0.382 (-0.167, 0.786)	0.347 (-0.191, 0.767)	0.5 (0.004, 0.827)	0.556* (0.035, 0.888)	0.469 (-0.063, 0.811)	0.429 (-0.088, 0.776)	-0.755* (-0.876, - 0.589)
Velocity step 1	-0.068 (-0.562, 0.442)	-0.003 (-0.512, 0.520)	0.014 (-0.404, 0.427)	-0.123 (-0.494, 0.363)	-0.135 (-0.587, 0.301)	-0.047 (-0.609, 0.399)	-0.078 (-0.559, 0.387)	-0.174 (-0.581, 0.303)	-0.118 (-0.488, 0.428)
Velocity step 2	0.753* (0.513, 0.892)	0.767* (0.547, 0.911)	0.799* (0.528, 0.946)	0.733* (0.446, 0.908)	0.675* (0.303, 0.872)	0.727* (0.276, 0.912)	0.782* (0.495, 0.908)	0.732* (0.504, 0.873)	-0.532* (-0.809, 0.051)
Velocity step 3	0.363	0.244	0.298	0.376	0.396	0.339	0.327	0.385	-0.522*

	(-0.381, 0.78)	(-0.45, 0.752)	(-0.21, 0.77)	(-0.258, 0.809)	(-0.245, 0.821)	(-0.257, 0.774)	(-0.337, 0.730)	(-0.298, 0.783)	(-0.813, - 0.075)
Rear block clearance	0.374	0.437	0.277	0.159	0.547*	0.647*	0.487	0.362	-0.419
relative step length	(-0.057, 0.700)	(-0.043, 0.738)	(-0.315, 0.762)	(-0.383, 0.632)	(0.205, 0.809)	(0.326, 0.858)	(0.064, 0.795)	(-0.078, 0.709)	(-0.717, 0.061)
Relative step length step 1	0.192 (-0.299, 0.667)	0.29 (-0.2, 0.726)	0.097 (-0.45, 0.723)	-0.053 (-0.559, 0.582)	0.25 (-0.145, 0.628)	0.356 (-0.016, 0.718)	0.231 (-0.265, 0.700)	0.093 (-0.386, 0.587)	-0.124 (-0.525, 0.297)
Relative step length step 2	0.393 (-0.281, 0.786)	0.473 (-0.217, 0.817)	0.38 (-0.331, 0.816)	0.216 (-0.45, 0.732)	0.44 (-0.157, 0.764)	0.543* (-0.012, 0.805)	0.441 (-0.251, 0.799)	0.302 (-0.386, 0.709)	-0.375 (-0.755, 0.310)
Relative step length step 3	0.356 (-0.329, 0.768)	0.397 (-0.265, 0.793)	0.37 (-0.355, 0.86)	0.226 (-0.5, 0.81)	0.436 (-0.111, 0.753)	0.533* (-0.023, 0.820)	0.404 (-0.27, 0.778)	0.284 (-0.369, 0.703)	-0.278 (-0.741, 0.487)
Modified rear block clearance time	-0.178 (-0.65, 0.405)	-0.032 (-0.550, 0.523)	-0.156 (-0.59, 0.304)	-0.233 (-0.630, 0.259)	-0.101 (-0.638, 0.434)	-0.056 (-0.583, 0.450)	-0.125 (-0.627, 0.398)	-0.19 (-0.669, 0.342)	0.593* (0.274, 0.819)

Flight time step 1	0.181 (-0.255, 0.558)	0.143 (-0.262, 0.515)	0.195 (-0.246, 0.656)	0.211 (-0.283, 0.635)	0.167 (-0.302, 0.636)	0.184 (-0.295, 0.671)	0.187 (-0.281, 0.620)	0.201 (-0.316, 0.602)	0.204 (-0.374, 0.620)
Flight time step 2	0.128 (-0.503, 0.591)	0.075 (-0.516, 0.508)	0.01 (-0.509, 0.518)	-0.028 (-0.597, 0.521)	0.269 (-0.204, 0.641)	0.311 (-0.12, 0.647)	0.128 (-0.417, 0.550)	0.08 (-0.488, 0.540)	-0.144 (-0.633, 0.318)
Flight time step 3	-0.04 (-0.421, 0.340)	-0.003 (-0.382, 0.351)	0.034 (-0.512, 0.580)	-0.136 (-0.604, 0.417)	0.104 (-0.294, 0.453)	0.261 (-0.175, 0.583)	0.058 (-0.381, 0.447)	-0.081 (-0.479, 0.342)	0.103 (-0.410, 0.591)
First contact time	0.21 (-0.420, 0.729)	0.234 (-0.517, 0.757)	0.04 (-0.486, 0.574)	-0.022 (-0.54, 0.578)	0.358 (-0.248, 0.838)	0.377 (-0.198, 0.861)	0.244 (-0.371, 0.757)	0.2 (-0.450, 0.717)	-0.231 (-0.656, 0.284)
Second contact time	-0.17 (-0.793, 0.488)	-0.07 (-0.780, 0.534)	-0.142 (-0.711, 0.402)	-0.311 (-0.791, 0.275)	-0.108 (-0.719, 0.474)	-0.007 (-0.62, 0.54)	-0.146 (-0.044, 0.347)	-0.281 (-0.819, 0.356)	-0.017 (-0.602, 0.714)
Third contact time	0.331 (-0.303, 0.748)	0.403 (-0.293, 0.773)	0.389 (-0.227, 0.758)	0.287 (-0.232, 0.688)	0.254 (-0.489, 0.685)	0.314 (-0.427, 0.72)	0.312 (-0.385, 0.717)	0.242 (-0.372, 0.692)	-0.05 (-0.624, 0.675)

Fourth contact	0.129	0.016	0.074	0.186	0.097	0.007	0.017	0.114	-0.158
time	(-0.463,	(-0.565,	(-0.472,	(-0.304,	(-0.449,	(-0.547,	(-0.578,	(-0.452,	(-0.754,
	0.712)	0.648)	0.748)	0.773)	0.678)	0.653)	0.687)	0.718)	0.411)

5.6 Discussion

It was hypothesised that IMTP variables would relate to stride length and velocity in step kinematics over the first three steps. This hypothesis can be rejected, as relationships were not observed in all three steps. Large relationships between IMTP variables and velocity and relative step length during the sprint start were determined during this study. The very large correlation between modified rear block clearance velocity and 0 – 5 time ($r = -0.755$, $p = 0.001$) detail that faster sprinters had a higher velocity when their rear foot exited the back block, and this is supported further by the large relationship between modified rear block clearance time and 0 – 5 m. Once the sprinters hand leaves the ground, faster athletes are quicker at getting their foot from the rear block to make the first foot contact. Interestingly, the velocity of steps 2 and 3 reported large relationships with 0 – 5 m time, while velocity of the step 1 was a small correlation ($r = -0.188$, $p = 0.674$) to 0 – 5 m time. On further examination of the 95% CIs for both correlations between velocity of steps 2 and 3 and 0 – 5 m time, the CIs cross or almost cross zero (95% CIs: -0.809 to 0.051, -0.813 to -0.075, respectively). Therefore, we can justifiably reject these relationships due to the wide CIs, and the fact they cross zero. The very large relationships observed between modified rear block clearance velocity and 0 – 5 m time may have occurred because the initial movement of the rear foot from the back block to first touchdown involves the highest increase in velocity of all the steps, the subsequent steps (velocity of steps 1, 2 and 3) have relatively weaker relationships with the outcome (0 – 5 m) since the modified block clearance velocity has such a strong relationship. Velocity during the sprint start should increase with each step in a gradual controlled effort (Mann and Murphy 2015). An elite male 100 m sprinter can generate over 4 m/s at ground touchdown when exiting the blocks. At step 1 this can increase to 6 m/s and step 2 further increases to around 7 m/s (Mann and Murphy 2015). Therefore, by step 3 the sprinter has developed over half of his maximum velocity. The lack of relationships and the presence of spurious relationships observed between velocity of steps 1, 2 and 3 and 0 – 5 m time could be explained by sub-optimal techniques of some of the athletes who participated in this study. For example, on further individual analysis of the athlete's performances, seven of the athlete's

velocities slightly decreased between steps 2 and 3 (e.g. step 2 = 5.48 m/s, step 3 = 5.32 m/s). The lack of increase in velocity from step 2 to 3 could be the result of a sub-optimal technique being used by the athlete, and could be a limitation of this study. While national and international level athletes were recruited, the level of performance did not guarantee the technical proficiency of the participants. This finding identifies the importance of coaches ensuring that their athletes are in the optimal position in the blocks to accelerate most effectively from the blocks, with effective technique. Without this, athletes may be underperforming in the start and may be unable to express their levels of strength efficiently and effectively to aid performance.

Force at 100 ms resulted in a large relationship with modified rear block clearance velocity ($r = 0.556$, $p = 0.031$). Athletes with the ability to produce larger amounts of force in shorter periods of time (≤ 100 ms) generally had a superior modified rear block clearance velocity. Small or moderate correlations were observed between IMTP variables and velocity of step 1 or 3. Conversely, velocity of step 2 resulted in very large relationships with all IMTP variables except for IMP 0 – 200 ms, which resulted in a large relationship ($r \geq 0.675$, $p \leq 0.006$). Most previous research has focused on examining block clearance velocity (Bezodis *et al.* 2019), which combines actions of both sides of the body. Results detail that the actions on opposing sides of the body are different and research should consider the reasons for these differences. Again, poor technique and ineffective acceleration from some athletes could explain the confounding results observed.

Referring back to the deterministic model of the sprint start (figure 5.1), velocity is a product of step length and step frequency. IMP 0 – 200 ms and force at 100 ms resulted in large correlations with rear block clearance relative step length. Sprinters that produced larger force, also had a larger relative step length. Further, force at 100 ms also resulted in large correlations with relative step lengths of steps 2 and 3, but not with relative step length of step 1; a similar pattern to velocity correlations. On examination of the CIs or relative step lengths 2 and 3 and force at 100 ms, the CIs cross zero (95% CIs: -0.012 to 0.805, -0.023 to 0.82 respectively), therefore, these wide CIs that cross zero can be rejected. On further examination of individual performance, three of the athletes had their 1st/2nd

relative step lengths shorter than their 2nd/3rd relative step lengths (e.g. relative step length 2 = 141 cm, relative step length 3 = 135 cm). This is indicative a sub-optimal technique, and could explain the confounding results observed in relation to step length. Maćkała *et al.* (2015) reported that stride length relative to leg length in sprinters was very largely correlated with 10 m time ($r = 0.70$). The authors compared high performance sprinters to a group of students, and noted that the sprinters had significantly longer step lengths during the acceleration phase and increased strength in their lower extremities, developed over a minimum of 5 years of training. This resulted in greater IMP in the push-off, and consequently a longer step length among the sprinters compared with the students (2015). Mann and Murphy (2015) noted that coaches should focus on ensuring that step length proceeding block clearance gradually increases, to allow for optimal performance.

Stride length is a complex kinematic variable, that depends on many factors including leg length, muscle structure, reflex mechanisms and GRF production (Coh *et al.* 2007). When examining correlations of step frequency, the factors of contact time and flight time must be examined. Small correlations were observed between 0 – 5 m, flight times and contact times and IMTP variables. Step frequency is associated with fast force production during ground contact and increased cadence requiring neuromuscular adaptations (Salo *et al.* 2011). A higher step frequency requires faster production of cross bridges within the muscles, and therefore need a high rate of neural activation (Heglund and Taylor 1988), which was not measured in this study. Sprinters use two different strategies to increase their running speed. Up to ~ 7 m/s, running speed increases by exerting large forces during the ground contact, which relates to increases in stride length, such as the 0 – 5 m segment observed in this study (average velocity at step 3 = 5.7 ± 0.33 m/s). Above ~ 7 m/s the strategy shifts to increasing stride frequency by swinging the legs more rapidly through the air (Weyand *et al.* 2000, Dorn *et al.* 2012).

Strong relationships have been reported between different measures of strength and sprint performance. Nagahara *et al.* (2014) reported moderate to large correlations between acceleration and the SJ from the 6th (8.3 ± 0.4 m mark) to the 10th steps (15.5 ± 0.7 m mark) and the CMJ from the 5th ($6.6 \pm$

0.4 m mark) to the 11th steps (17.5 ± 0.8 m mark). This is supported by Maulder *et al.* (2006) who reported that CMJ and SJ average power (W/kg), average force (N) and peak power (W/kg) very largely correlated with 10 m time ($r \geq -0.7$). Wisløff *et al.* (2004) reported large correlations between 10 yard sprint time and maximal squat 1RM/BM ($r = 0.54$, $p = 0.02$) among a group of soccer players. Further, Maćkała *et al.* (2015) reported large or very large correlations between 10 m time and the standing long jump, standing five jumps, standing ten jumps and speed in 10 m ($r = 0.66$, $r = 0.72$, $r = 0.66$ and $r = 0.72$ respectively). In addition, sprinters with a higher level of maximum strength generated more powerful horizontal jumps. This previous research has reported relationships between dynamic strength and jump performance and sprint acceleration. Among Rugby League players, West *et al.* (2011) reported moderate correlations between CMJ height and RPF ($r = 0.45$) and peak RFD ($r = 0.39$). Further, among football players and sprinters, CMJ peak power was very largely correlated to IMTP PF ($r = 0.75$). High expressions of force are required in the initial start phase, and strength characteristic measurements derived from the IMTP are significantly related to determinants of 0 – 5 m acceleration.

This is the first study to identify whether isometric strength qualities related to sprint performance had any meaningful relationships with sprinting kinematics from the blocks and over the first 5 m. Further analysis identified that the IMTP and its associated variables relate to velocity and step length from the blocks over the first 5 m, with small relationship observed with step frequency measures of flight time or contact time. It is believed that a greater training emphasis is placed on methods that attempt to increase step length (Murphy *et al.* 2003), possibly because step frequency is more difficult to improve than step length (Murray *et al.* 2005). Athletes reliant on step length need to retain their strength throughout a season, and maintain the necessary hip flexibility to produce long steps (Salo *et al.* 2011). By comparison, athletes reliant on stride frequency, require a high rate of neural activation so they can produce a quick cadence (Salo *et al.* 2011). Further analysis identified that some athletes were possibly using a sub-optimal technique to accelerate. Coaches should ensure that kinematic factors such as step length gradually increase throughout the acceleration phase from step 1 while

contact time gradually decreases. Without an optimal technique, athletes may be unable to express their strength effectively and this could lead to a decrease in performance. Therefore, stronger athletes with higher force potential can only achieve better performances when force is applied with optimal timing and direction (Aerenhouts *et al.* 2012). Off-track testing protocols that identify an athlete's strength and weaknesses related to the sprint acceleration may assist coaches in training sprinters. It is unknown however, from the results of this study whether changes in block settings or technique would allow athletes to express their strength more effectively. Since instrumented blocks were not used, it was not possible to obtain true block clearance time and velocity, therefore modified versions of these variables were examined.

5.7 Practical Applications

Higher measures of PF and time specific force values displayed large or very large relationships with modified rear block clearance velocity, velocity of step 2 and rear block clearance step length, which reaffirms the usefulness of isometric testing for the track & field sprint population. Those athletes who produced higher forces had higher velocities and longer rear block clearance relative step lengths. Sprinters and coaches should be aware of the different strength capabilities required for effective acceleration and understand that there is an underlying strength quality associated with step length, while step frequency had no association with strength as measured in this study. If increasing step length is a technical goal, maximal strength training should be considered as an additional training method.

Chapter 6: Study 5 - The Relationship between the Isometric Squat and Stretch Shortening Cycle Function and Sprint Performance in Hurling Players

Brady, C.J., Harrison, A.J., Flanagan, E.F., Haff, G.G., Comyns, T.M.
2019. The relationship between the isometric squat and stretch shortening
cycle function and sprint performance in hurling players. *Journal of Sports
Science* (Under review)

6.1 Preface

Having established the relationship between isometric strength and sprint performance in track and field sprinters, the next step in this thesis was to establish the relationship between isometric strength and sprint performance in field sport athletes. Hurling is a national sport of Ireland and speed has been established as an important component for success in hurling, yet there is limited research on hurling players. Isometric testing is increasing in its applications in field sports such as hurling, and the relationship between isometric strength and sprint performance among hurling players needs to be examined. An U21 male hurling team was recruited for this study. Due to time constraints, there was only enough time to perform one isometric test. Study 2 detailed that there were no significant differences between force measures from the IMTP and ISqT among male athletes. Having consulted with the hurling teams S&C coach, it was decided that the ISqT would be the preferred test with this cohort as it best replicated the players training background. Further, there is limited research on the relationship of the ISqT and sprint performance in field sport athletes. On the day of testing, the teams S&C coach requested examination of CMJ height and the RSI. Previous research has identified moderate and large correlations between the CMJ and RSI and sprint performance among track and field sprinters, rugby and soccer players. No previous research had examined this relationship among hurling players. On the day of testing, the players' also performed CMJs and the 10/5 RJT. I decided to include the results of these tests in the analysis and this allowed for analysis of the relationship between the ISqT, CMJ and RSI and sprint performance and assessment of whether these tests could distinguish between performance levels. These relationship had never been examined in hurling players previously and this research would add to the literature. Further, having this large amount of data, additional analysis was performed, determining if PCA could be used to reduce the dataset to a collection of variables related to sprint performance. This paper provides practical applications for coaches and practitioners on the different strength and stretch shortening cycle (SSC) functions that compose speed for hurling players.

6.2 Abstract

The aim of this study was to examine the relationship between the ISqT, CMJ, and RSI and sprint performance in hurling players. The secondary aims were to determine if these tests could distinguish between sprint performance levels and if PCA could be used to reduce the dataset to independent factors. Twenty-six male under-21 hurling players performed ISqTs, CMJs, the 10/5 RJT and 30 m sprints with splits times at 5 m, 10 m, 20 m and 30 m. Moderate correlations were observed between force at 100 ms and 0 – 5 m and 5 – 10 m, moderate and large negative correlations between CMJ and all splits and large correlations between RSI and splits over 5 m. Force at 100 ms distinguished between performance levels from 0 – 5 m, CMJ from 10 – 20 m and RSI from 20 – 30 m; the faster athletes produced significantly higher force, JHs and RSI scores. The PCA identified three principal components (PCs) explaining 86.1% of the variation in the dataset. These were sprint times and SSC capabilities and sprint times (33.3%), time specific force values (29.9%) and absolute and relative strength (22.8%).

6.3 Introduction

Hurling is a 15-a-side intermittent stick and ball team sport considered to be one of the fastest field sports in the world and is a national sport in Ireland (Reilly and Collins 2008). Elite players, perform intense activity on average every 22 seconds, which leads to an average of 62 high intensity accelerations being performed in each game (Collins *et al.* 2018). Superior acceleration over 20 m results in better outcomes in both offensive and defensive situations as accelerations occur close to the hurling ball, and can determine the outcome of crucial events during the game (Reilly and Collins 2008).

Sprinting requires high levels of acceleration and high levels of strength to overcome inertia. The relationship between dynamic strength and sprint performance indicates that stronger field sport athletes are superior sprinters (Wisløff *et al.* 2004, Cronin and Hansen 2005, Comfort *et al.* 2012). The relationship between isometric force production, measured using the IMTP, and sprint performance has been examined in team sport athletes (Thomas *et al.* 2015a, Wang *et al.* 2016), however there is a lack of research examining

this relationship using the ISqT. Due to the lack of significant difference between the force measures achieved during an IMTP and ISqT (Brady *et al.* 2018b), it is likely that similar relationships exist with sprint performance. For example, in rugby players, early phase maximal force (≤ 100 ms) measured during the ISqT has been reported to be largely related to sprint performance (5 m, $r = -0.63$ and 20 m, $r = -0.54$) (Tillin *et al.* 2013). When the athletes were subdivided into faster and slower groups based on 5 m sprint time ($<$ or ≥ 1 s) the faster group exhibited significantly greater force generation in the first 150 ms (33 – 67%). While these data are important, there is no known research on the relationship between ISqT strength and acceleration in hurling players.

During match play, hurlers generate rapid movements such as jumps and sprints and these movements are underpinned by the ability to produce high force in a short time (Reilly and Collins 2008). Among professional Rugby League players, CMJ height has been reported as a large correlation with 5 m ($r = -0.60$), 10 m ($r = -0.62$) and 30 m ($r = -0.56$) sprint times (Cronin and Hansen 2005). Among elite soccer players, a very large correlation was reported between vertical jump height (JH) and 10 m ($r = -0.72$) sprint time, and a large correlation with 30 m ($r = -0.60$) sprint time (Wisløff *et al.* 2004). Large correlations were detailed between CMJ height and 20 m ($r = -0.54$) and 30 m ($r = -0.55$) in U21 soccer players (López-Segovia *et al.* 2011). The relationship between the RSI and sprint performance in sprint athletes has produced contrasting results. In male sprinters, a large correlation was reported between sprint performance over 10 m ($r = -0.65$) and a moderate correlation 30 m ($r = -0.42$) and the drop jump (DJ) (Smirniotou *et al.* 2008). These relationships among team sport athletes appear to be overlooked, however a large correlation was detailed between RSI in the DJ (from a 40 cm box) and 10 m time ($r = -0.60$) (Cunningham *et al.* 2016). These results illustrate the difficulty in identifying how performances can be related to one another.

The 1RM back squat (O'Donoghue *et al.* 2004, McIntyre 2005), CMJ and RSI (Byrne *et al.* 2017) have also been previously used for various reasons, such as individualising training programmes for and monitoring of hurling athletes. Typically, strength assessments, such as 1RM testing, are skills

therefore, using multiple strength measures, including isometric testing, may be better for determining true measures and changes in strength (Buckner *et al.* 2017). The athlete's PF capacity and the RFD can be determined from the force-time curve. Jumping ability and reactive strength have been reported as essential characteristics of hurling players due to the fast paced nature of the game (McIntyre 2005, Duncan 2006). The CMJ and RSI tests examine an athlete's SSC function and SSC can be classified as fast, (contact time < 250 ms) or slow, (contact times > 250 ms) (Schmidtbleicher 1992).

When analysing sports performance, PCA can be useful for analysing large multi-dimensional datasets. PCA can reduce the dimensionality of the data by grouping variables together to form a smaller number of uncorrelated PCs (Parmar *et al.* 2017). PCA has rarely been used in performance analysis research but it has the potential to identify combinations of variables that determine successful performance. Sprint performance is complex and multi-faceted, therefore success can be linked to many variables, which may be inter-correlated. PCA has the advantage of identifying uncorrelated groups of variables (PCs) which account for the variance in the dataset.

While investigations have examined the strength, sprint and SSC function capabilities in hurling players, few if any, studies have investigated the relationship between ISqT force-time curve characteristics, CMJ, RSI and sprint performance in U21 elite hurling players. No study to date, determined whether any of these tests can differentiate between sprint ability performance levels and whether PCA can reduce force generating and SSC capabilities into orthogonal components. The primary aim of this study was to examine the relationship between the ISqT, CMJ, RSI and sprint performance in hurling players. The secondary aims were to determine if the tests could distinguish between performance levels and if PCA could be used to improve sprint performance by improving a collection of variables instead of analysing variables in isolation. It was hypothesised that the ISqT, CMJ and RSI would relate to different phases of the 30 m sprint and that each test would distinguish between performance levels of different phases of the sprint.

6.4 Methods

6.4.1 Participants

Twenty-six U21 male (age, 19.2 ± 0.8 y; height, 1.81 ± 0.05 m; and body mass, 78.8 ± 6.4 kg) inter - county hurling players took part in the present study. All athletes had at least six months of strength training experience. All participants were familiarised with the ISqT, CMJ and the 10/5 RJT prior to the testing session. Ethical approval was provided by the institution's Research Ethics Review Board. Athletes provided informed consent in writing in compliance with the Declaration of Helsinki.

6.4.2 Procedures

6.4.2.1 Isometric Squat

Participants completed a general warm-up (Figure 6.1) and then were set in the correct position, adopting knee angles of $138 \pm 5^\circ$ and hip angles $139 \pm 3^\circ$. This knee angle was selected as greater PF and RFD measures are observed at higher knee angles (120° v 90°) (Palmer *et al.* 2018). Angles were measured using a hand-held goniometer; foot width was measured and remained constant between trials. Participants were required to maintain their individually established position throughout the test. A standardised ISqT warm up was undertaken in accordance with previous literature (Brady *et al.* 2018b). Participants then rested for 2 minutes before completing their maximum efforts. Participants completed 3 maximal efforts with each lasting 5 seconds and a 2-minute rest between trials. For each trial, participants were instructed to “push as hard and as fast as you can” to ensure maximal force was achieved (Haff *et al.* 2015). Participants were instructed to get ready, and then were given a countdown of “3, 2, 1, push!”. Verbal encouragement was provided during each trial. Participants completed a fourth trial if the effort was not deemed maximum, or if there was a greater than 250 N difference between efforts (Kraska *et al.* 2009).

All isometric testing was conducted on a custom-made isometric rack (Sorinex inc., Lexington, SC), allowing the placement of the bar at 0.5 cm intervals and permitting the desired position for each participant. The rack was anchored to the floor above Kistler 9287 CA force platform (Winterthur,

Switzerland), which sampled at 1000 Hz. All unfiltered force–time curves were analysed using a custom-built spreadsheet to determine specific force–time characteristics. The collection period for each trial was 12 seconds, and a baseline force was measured for 3-seconds of quiet standing prior to the push (Brady *et al.* 2018b). The criterion onset threshold and onset of the contraction were defined as the point where the force exceeded 5 SD from baseline (Dos’Santos *et al.* 2017a). PF was reported as maximum force during the 5 second trial minus the participant’s body weight. PF was also reported relative to body mass (N/kg). Since contact times during sprinting range from ~ 100 – 200 ms (Mero *et al.* 1992), these time points were used when selecting isometric variables of time specific force epochs, RFD and IMP. Force at 100, 150 and 200 ms from the initiation of the squat. RFD ($\Delta\text{Force}/\Delta\text{Time}$) was applied to specific time intervals (0 – 100, 0 – 150 and 0 – 200 ms) previously reported in the literature (Haff *et al.* 2015). IMP was determined as average force divided by the change in time over 100 and 200 ms.

6.4.2.2 Countermovement Jump Test

Participants started their jump assessment after the ISqT and completed 3 jumps separated by 1-minute rest. Jumps were measured using an Optojump system (Microgate, Bolzano, Italy). Participants performed jumps with arms akimbo to limit upper limb contributions and were instructed to jump for maximal height. JH was determined from flight time (FT) using the equation $JH = (9.81 \times FT^2)/8$ (Bosco *et al.* 1983).

6.4.2.3 Repeated Jump Test

Participants performed 1 set of the 10/5 RJT test, using the Optojump system, which provides a valid and reliable measure of reactive strength (Harper 2011). The athletes performed a single CMJ and upon landing, immediately transitioned into a series of 10 repeated bilateral jumps with arms akimbo, focusing on maximal height and minimal contact time. Further instruction was given to “minimise ground contact time”, “maximise jump height”, “imagine the ground as a hot surface” and “legs like a stiff spring” (Flanagan and Comyns 2008). From the ten jumps recorded, RSI was measured (JH divided

by contact time) and the five best hops, as determined by the highest RSIs, in each trial were used to calculate average values for contact time, JH and RSI (Harper 2011). JH was calculated using the same method described for the CMJ.

6.4.2.4 30 m Sprint Test

After a ten-minute rest, participants then completed a sprint warm up including 2 by 15 m standing starts. All participants completed 3 maximal effort 30 m sprints from a standing start with six minutes of recovery between sprints. Dual-beam timing gates (Microgate, Bolzano, Italy) were positioned at 5, 10, 20 and 30 m. Split times from 0 – 5 m, 5 – 10 m, 10 – 20 m, 20 – 30 m and overall 30 m were recorded. Timing was initiated at the instant the athlete's foot left a start pad positioned underneath their rear foot, using a previously validated protocol that synchronised timing gates to the Optojump system (Healy *et al.* 2016b).

6.4.3 Statistical Analyses

All force-time data were analysed using a custom spreadsheet. Normality was assessed for all variables using the Shapiro-Wilk statistic and were determined to be normally distributed ($p > 0.05$). Relationships between isometric force-time curve characteristics, CMJ and RSI and sprint times were determined by Pearson product-moment correlation using SPSS software (version 22.0, IBM Corp, Armonk, NY). The best repetitions based on isometric PF and 30 m sprint time were used for analysis (Beattie *et al.* 2017b). Correlations were evaluated as: small (0.1–0.29), moderate (0.3–0.49), large (0.5–0.69), very large (0.7–0.89), nearly perfect (0.9–1.0), and perfect (1.0) (Hopkins *et al.* 2009). Fisher's r-Z transformation was used to facilitate interpretation of the difference between two correlation coefficients. Reliability for isometric variables was calculated by determining the CV, calculated as the TE and expressed as a CV%, the ICC and 95% CIs using a Microsoft Excel spreadsheet (Hopkins 2015). Acceptable reliability was defined as $ICC \geq 0.8$ and $CV \leq 10\%$ (Hopkins 2000). Based on the 95% CI of the ICC estimate, values less than 0.5, between 0.5 and 0.75, between

0.75 and 0.9, and greater than 0.90 are indicative of poor, moderate, good, and excellent reliability, respectively (Koo and Li 2016).

Participants were grouped into quartiles with respect to force (100 ms), CMJ and RSI to investigate sprint ability of those with the highest force producing/CMJ height/RSI scores (top quartile; $n = 7$) and lowest force producing/CMJ height/RSI scores (bottom quartile; $n = 7$) (Beattie *et al.* 2017b). Two-tailed independent-samples t tests assessed differences between group means for force (100 ms), CMJ and RSI, together with Holm's sequential Bonferroni method for correcting Type I error (Holm 1979). Effect sizes (Hedges g) were calculated to determine the magnitude of differences between groups and was interpreted using Cohen's scale as trivial ($g < 0.2$), small ($0.2 \leq g < 0.6$), moderate ($0.6 \leq g < 1.2$) and large ($1.2 \leq g < 2.0$) and very large (≥ 2.0) (Cohen 1988).

PCA with orthogonal rotation (varimax method), was used to provide insight on the structure of the sprint time, isometric strength and SSC capabilities and to reduce the dimensionality of the dataset. The Kaiser-Meyer Olkin measure was then used to determine the sampling adequacy and the number of components retained in the analysis was based on eigenvalues > 1 .

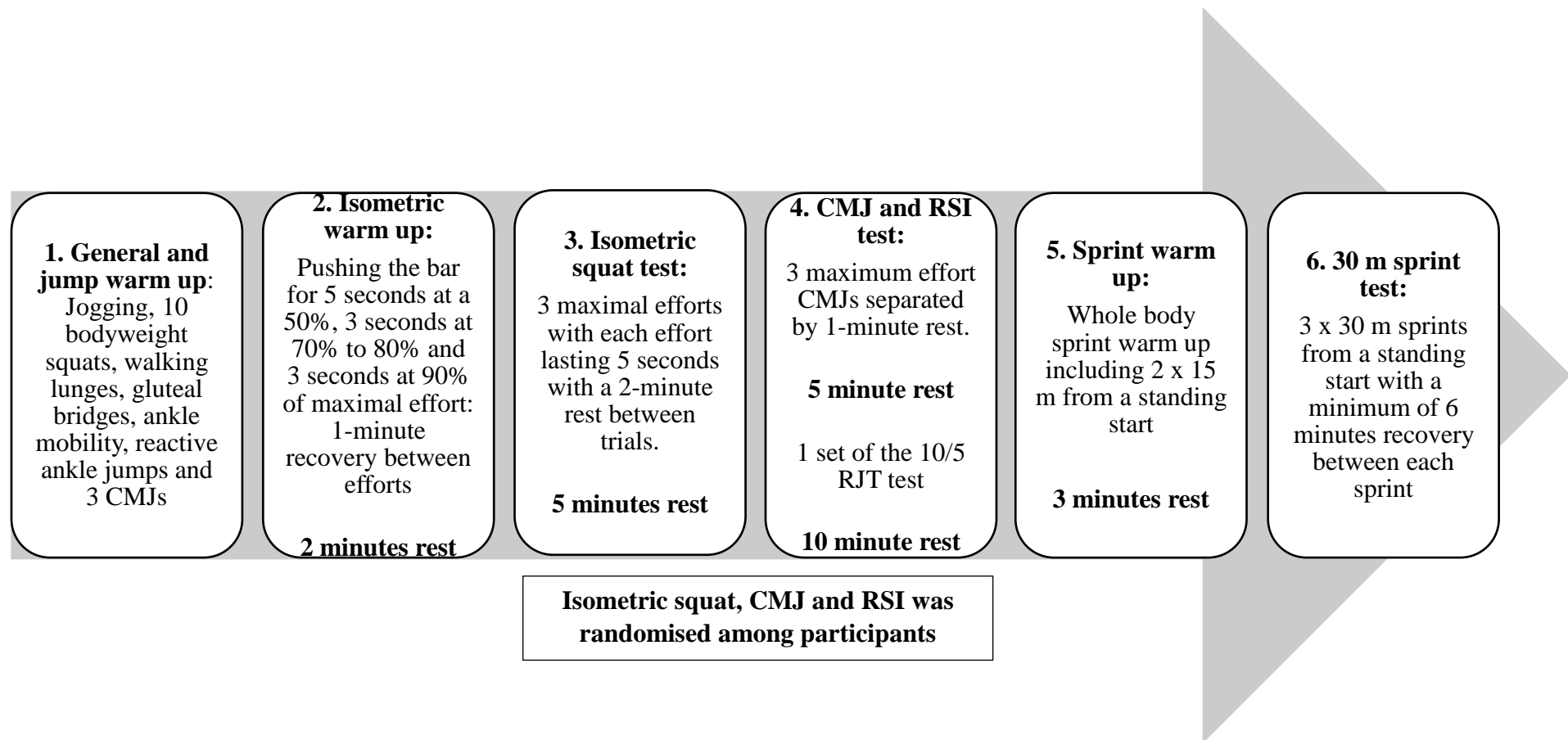


Figure 6.1 - Flow chart detailing the study design

6.5 Results

Descriptive statistics (mean \pm SD) for all variables are presented in Table 6.1 along with reliability results. All variables displayed ‘good’ or ‘excellent’ reliability with the lower bound 95% CI \geq 0.81 with the only exception being 0 – 5 m time displaying ‘moderate’ reliability with the lower bound 95% CI = 0.74 (Koo and Li 2016). All measures of RFD and IMP (0 – 100 ms) were unreliable and therefore not used for further analysis.

6.5.1 Relationships with Sprint Performance

Correlations between ISqT, CMJ and RSI and sprint performance are detailed in Table 6.2. Force at 100 ms was moderately correlated with sprint times (0 – 5 m, 5 – 10 m and 0 – 10 m) (Figure 6.2). Since the strongest relationships were observed between force at 100 ms and sprint time, this variable was chosen for further analysis in determining if the test could distinguish between performance levels. CMJ height and 0 – 5 m time resulted in a moderate correlation. CMJ height and 5 – 10 m, 0 – 10 m, 0 – 20 m and 0 – 30 m times resulted in a large correlation. CMJ height and 10 – 20 m (Figure 6.3) and 20 – 30 m times resulted in very large correlations. A moderate correlation was reported between RSI and 0 – 10 m time and large correlations were observed between RSI and 5 – 10 m, 10 – 20 m, 20 – 30 m (Figure 6.4), 0 – 20 m and 0 – 30 m times.

Table 6.1 Descriptive Statistics and Within Session Reliability of ISqT, CMJ and Speed Splits Attaining a Criteria of an ICC ≥ 0.8 and a CV $\leq 10\%$ with 95% CIs

Variable	Mean \pm SD	ICC (95% CI)	CV% (95% CI)
ISqT			
PF (N)	1956 \pm 390	0.97 (0.94, 0.99)	3.5 (2.8, 4.9)
RPF (N/kg)	25.0 \pm 5.3	0.97 (0.94, 0.99)	3.5 (2.8, 4.9)
IMP (0 – 200 ms) (N.s)	162 \pm 42	0.95 (0.89, 0.98)	7.1 (5.5, 10)
Force at 100 ms (N)	856 \pm 243	0.92 (0.82, 0.96)	9.5 (7.4, 13.4)
Force at 150 ms (N)	1057 \pm 295	0.95 (0.89, 0.98)	6.7 (5.2, 9.4)
Force at 200 ms (N)	1180 \pm 290	0.93 (0.84, 0.97)	7.3 (5.7, 10.2)
Speed (s)			
0 – 5 m	1.115 \pm 0.039	0.87 (0.74, 0.94)	1.4 (1.1, 2.0)
5 – 10 m	0.749 \pm 0.023	0.91 (0.81, 0.96)	1.0 (0.8, 1.4)
10 – 20 m	1.264 \pm 0.041	0.96 (0.92, 0.98)	0.7 (0.5, 0.9)
20 – 30 m	1.189 \pm 0.044	0.96 (0.93, 0.98)	0.8 (0.6, 1.1)
0 – 10 m	1.864 \pm 0.057	0.92 (0.83, 0.96)	0.9 (0.7, 1.3)
0 – 20 m	3.128 \pm 0.093	0.96 (0.91, 0.98)	0.7 (0.5, 0.9)
0 – 30 m	4.317 \pm 0.135	0.97 (0.93, 0.98)	0.6 (0.5, 0.9)
CMJ JH (cm)	37.5 \pm 4.2	0.92 (0.84, 0.97)	3.4 (2.6, 4.6)
10/5 RJT			
RSI	1.72 \pm 0.33		
JH (cm)	31.3 \pm 4.1		
Contact time (s)	0.186 \pm 0.02		

CMJ = countermovement jump; CI = confidence interval; CV = coefficient of variation; ICC = intraclass correlation coefficient; IMP = impulse; JH = jump height; PF = peak force; RPF = relative peak force; RJT = repeated jump test

Table 6.2 Inter-correlation matrix between ISqT, CMJ and RSI and sprint performance measures

	0 - 5 m	5 - 10 m	10 - 20 m	20 - 30 m	0 – 10 m	0 – 20 m	0 – 30 m
Maximum Force (N)	-0.14 (-0.488, 0.266)	-0.105 (-0.412, 0.229)	-0.001 (-0.303, 0.301)	-0.002 (-0.273, 0.285)	-0.141 (-0.469, 0.184)	-0.085 (-0.395, 0.233)	-0.06 (-0.36, 0.257)
PF (N)	-0.163 (-0.507, 0.195)	-0.094 (-0.373, 0.219)	0.004 (-0.331, 0.318)	0.009 (-0.290, 0.303)	-0.152 (-0.477, 0.185)	-0.09 (-0.393, 0.227)	-0.06 (-0.363, 0.272)
RPF (N/kg)	-0.212 (-0.587, 0.198)	-0.044 (-0.337, 0.266)	0.019 (-0.316, 0.336)	0.036 (-0.321, 0.364)	-0.165 (-0.487, 0.169)	-0.092 (-0.421, 0.265)	-0.052 (-0.392, 0.288)
IMP (0 - 200 ms) (N.s)	-0.413 (-0.648, -0.137)	-0.223 (-0.544, 0.148)	-0.157 (-0.451, 0.122)	-0.165 (-0.469, 0.144)	-0.379 (-0.608, -0.093)	-0.299 (-0.563, 0.03)	-0.26 (-0.539, 0.032)
Force 100 ms (N)	-0.446 (-0.687, -0.147)	-0.407 (-0.638, -0.146)	-0.235 (-0.536, 0.107)	-0.163 (-0.477, 0.11)	-0.407 (-0.668, -0.124)	-0.318 (-0.594, -0.036)	-0.173 (-0.498, 0.1)
Force 150 ms (N)	-0.383 (-0.627, -0.081)	-0.183 (-0.517, 0.188)	-0.115 (-0.385, 0.146)	-0.128 (-0.394, 0.128)	-0.341 (-0.593, -0.053)	-0.257 (-0.532, 0.019)	-0.219 (-0.485, 0.057)
Force 200 ms (N)	-0.331 (-0.576, -0.043)	-0.149 (-0.477, 0.177)	-0.032 (-0.292, 0.196)	-0.049 (-0.335, 0.264)	-0.291 (-0.536, 0.013)	-0.191 (-0.479, 0.095)	-0.148 (-0.411, 0.147)
CMJ (cm)	-0.391 (-0.729, -0.03)	-0.613 (-0.839, -0.291)	-0.752 (-0.882, -0.516)	-0.706 (-0.863, -0.425)	-0.524 (-0.791, -0.152)	-0.649 (-0.856, -0.334)	-0.676 (-0.87, -0.352)

RSI	-0.364	-0.557	-0.565	-0.597	-0.482	-0.541	-0.566
	(-0.015, 0.162)	(-0.786, -0.272)	(-0.742, -0.295)	(-0.763, -0.340)	(-0.747, -0.174)	(-0.772, -0.253)	(-0.763, -0.299)

CMJ = countermovement jump; IMP = impulse; PF = peak force; RPF = relative peak force; RSI = reactive strength index. Results are presented as r (95% CI) with statistically significant correlations presented in bold

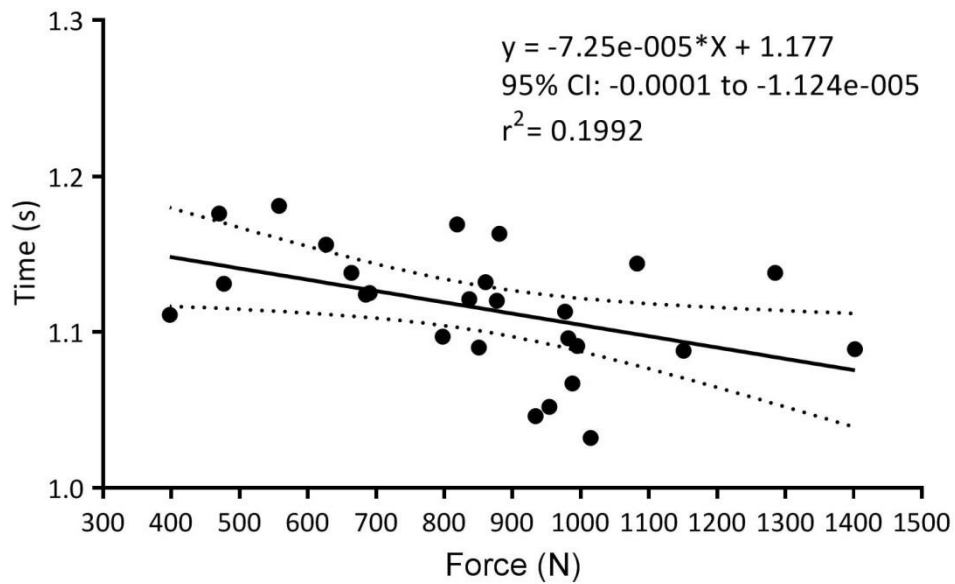


Figure 6.2 - Scatterplot correlative findings between ISqT force at 100 ms and 0 – 5 m time.

Note: Dashed line demonstrates 95% CI (1.123 to 1.232)

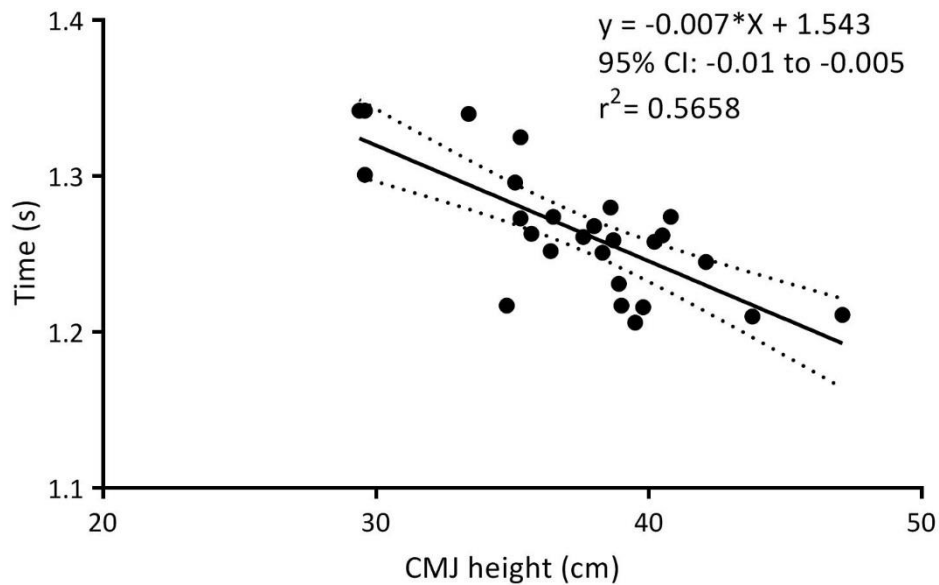


Figure 6.3 - Scatterplot correlative findings between CMJ height and 10 – 20 m time.

Note: Dashed line demonstrates 95% CI (1.44 to 1.646)

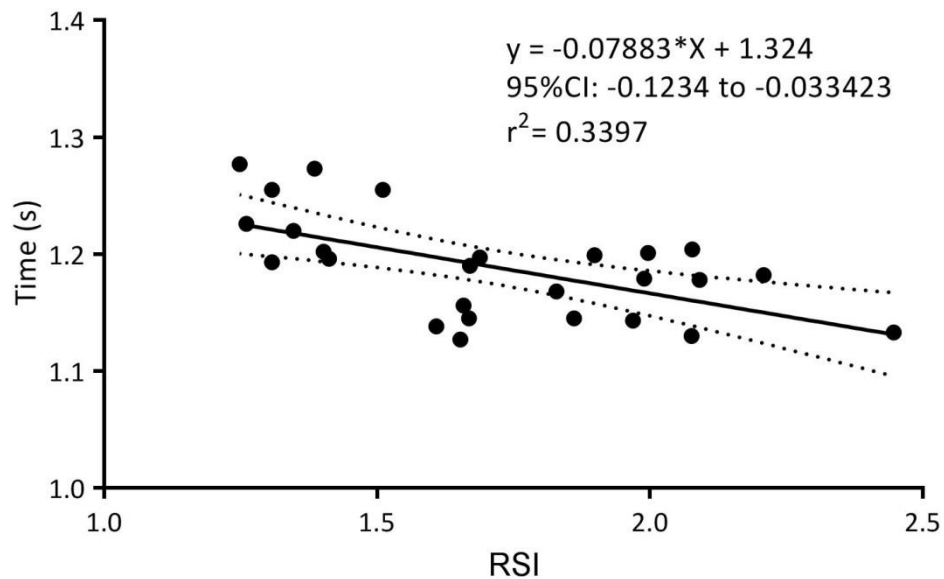


Figure 6.4 - Scatterplot correlative findings between RSI and 20 – 30 m time.

Note: Dashed line demonstrates 95% CI (1.246 to 1.402)

6.5.2 Distinguishing between Performance Levels

Differences between the top quartile performers (high force producing/CMJ height/RSI scores) and bottom quartile performers (low force producing/CMJ/RSI scores) in the ISqT (force at 100 ms), CMJ and RJT are presented in Table 6.3. A statistically significant difference and a very large effect size was reported between groups for force at 100 ms, therefore this method was able to distinguish between force at 100 ms strength levels. There was a significant difference and large effect size between groups at the 0 – 5 m split, with the athletes producing higher forces and running faster at this split. There was no significant difference between 5 – 10 m, 10 – 20 m and 20 – 30 m time splits, and effect sizes were moderate or small for these splits (Figure 6.5).

Table 6.3 Comparison between top quartile (highest force producing/CMJ/RSI scores) and bottom quartile (lowest force producing/CMJ height/RSI scores) athletes when split by ISqT force at 100 ms, CMJ and RSI and sprint performance

Measure	Top Quartile (n = 7)	Bottom Quartile (n = 7)	<i>p</i>	Hedges <i>g</i>	Effect size
Force at 100ms (N)	1131 ± 159	554 ± 109	< 0.001*	3.92	Very large
0-5 m (s)	1.093 ± 0.039	1.145 ± 0.027	0.048*	1.47	Large
5-10 m (s)	0.736 ± 0.027	0.760 ± 0.024	0.307	0.88	Mod
10-20 m (s)	1.255 ± 0.046	1.279 ± 0.029	0.524	0.58	Small
20-30 m (s)	1.178 ± 0.051	1.204 ± 0.033	0.524	0.57	Small
CMJ (cm)	42.0 ± 2.6	32.5 ± 2.8	< 0.0001*	3.29	Very large
0-5 m (s)	1.116 ± 0.032	1.136 ± 0.051	0.404	0.43	Small
5-10 m (s)	0.737 ± 0.02	0.760 ± 0.027	0.210	0.87	Mod
10-20 m (s)	1.239 ± 0.027	1.302 ± 0.046	0.038*	1.53	Large
20-30 m (s)	1.166 ± 0.029	1.222 ± 0.054	0.094	1.21	Large
RSI	2.13 ± 0.16	1.32 ± 0.06	< 0.0001*	6.49	Very large
0-5 m (s)	1.116 ± 0.037	1.147 ± 0.026	0.098	1.34	Large
5-10 m (s)	0.739 ± 0.016	0.77 ± 0.015	0.012*	1.25	Large
10-20 m (s)	1.25 ± 0.029	1.303 ± 0.035	0.018*	1.51	Large
20-30 m (s)	1.172 ± 0.03	1.235 ± 0.034	0.012*	0.82	Mod

Mod = moderate. Values are reported as mean ± SD. * Between-groups differences significantly different using Holm's sequential Bonferroni adjusted *p* value, *p* <0.05

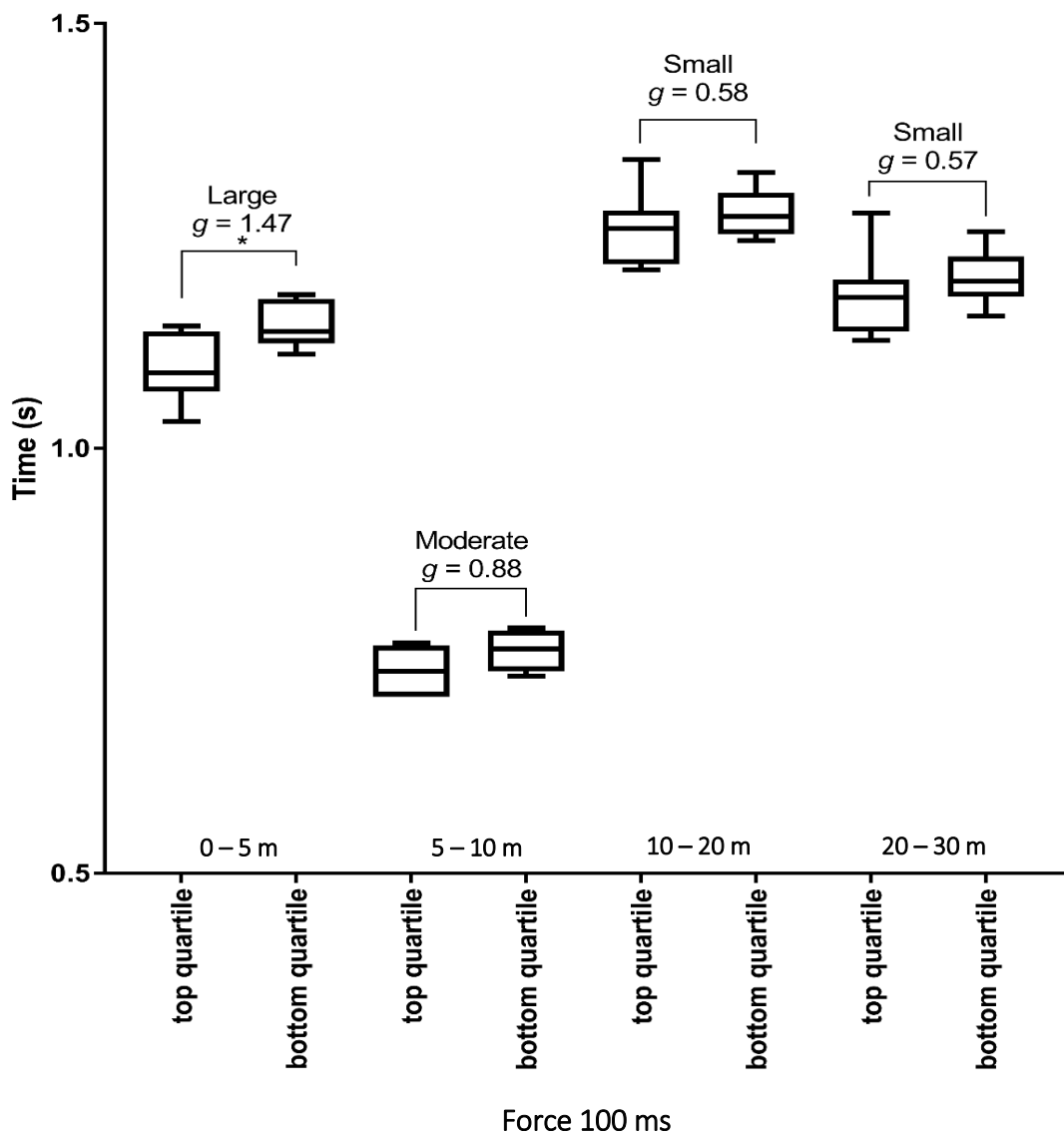


Figure 6.5 - Sprint split mean difference and magnitudes for athletes producing the highest force at 100 ms ($n = 7$; 1131 ± 159 N; top quartile) and those produces the lowest force at 100 ms ($n = 7$; 554 ± 109 N; bottom quartile) athletes measured during the ISqT

There was a significant difference and a very large effect size between groups for CMJ performance, therefore this method was able to distinguish between slow SSC function levels. There was only one statistically significant difference at the 10 – 20 m split and a large effect size, with the athletes with higher CMJ JH sprinting faster through this split. There was also a large effect size at the 20 – 30 m split but this was not significant (Figure 6.6). All other splits were small or moderate.

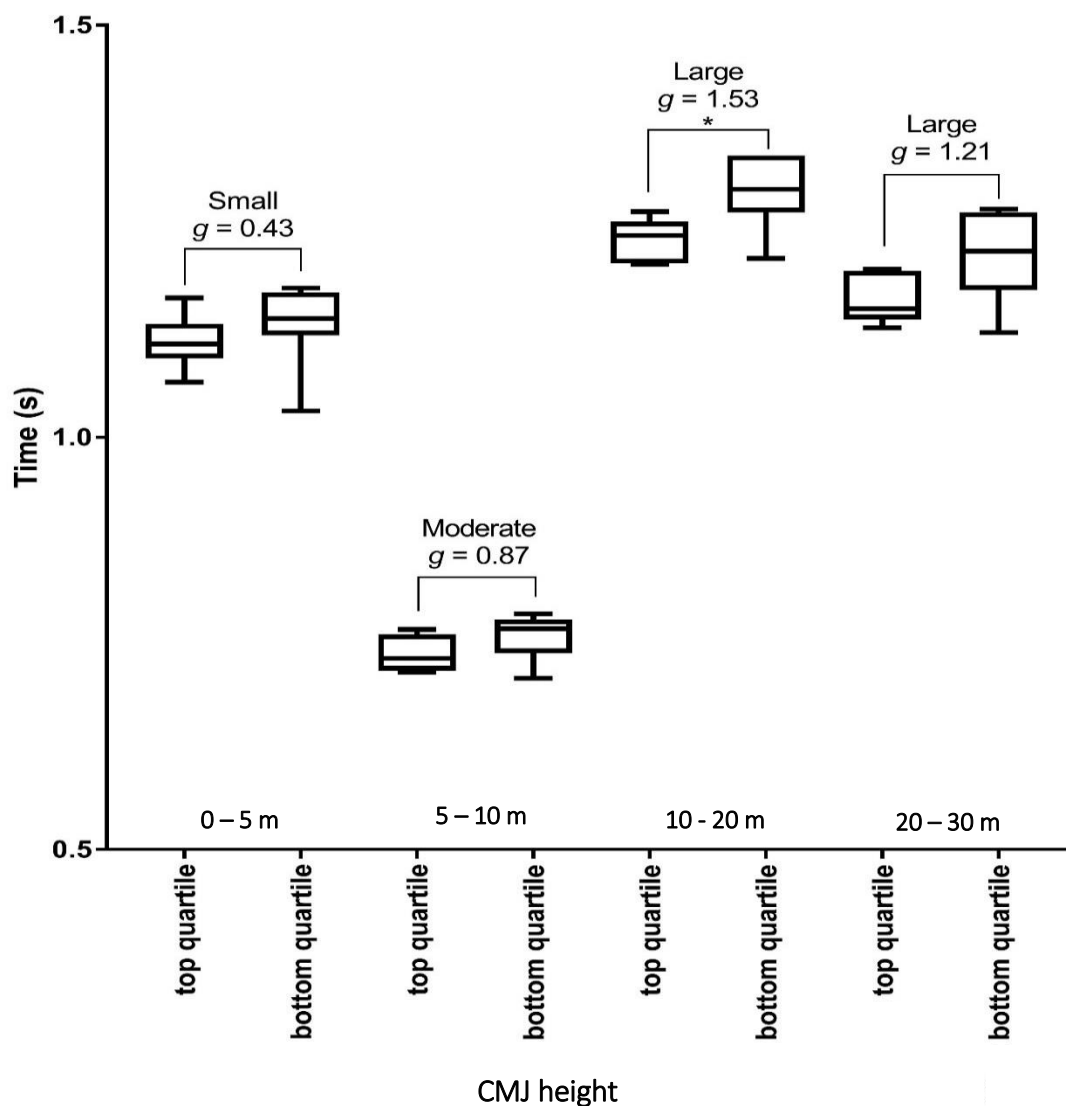


Figure 6.6 - Sprint split mean difference and magnitudes for highest CMJ height (n = 7; 42.0 ± 2.6 cm; top quartile) and lowest CMJ height (n = 7; 32.5 ± 2.8 cm; bottom quartile) athletes measured during the CMJ

A statistically significant difference and a very large effect size was reported between groups for RSI performance, therefore this method was able to distinguish between reactive strength ability levels. There were statistically significant differences at the 5 – 10 m, 10 – 20 m and 20 – 30 m splits, with effect sizes being moderate or large and the more reactive athletes were faster at each of these splits. There was no significant difference at the 0 – 5 m split, however there was a large effect size between groups (Figure 6.7).

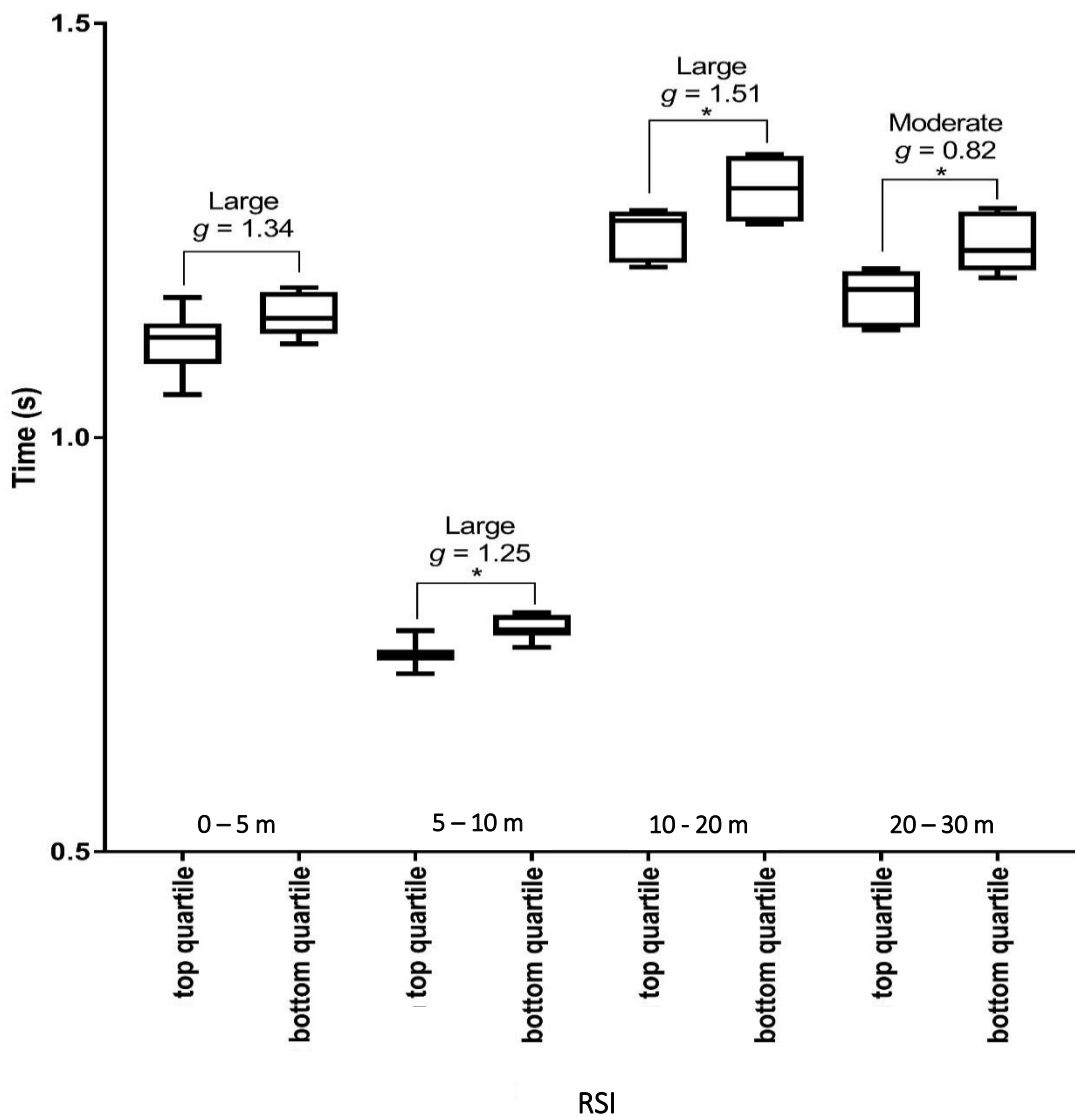


Figure 6.7 - Sprint split mean difference and magnitudes for most reactive ($n = 7$; 2.08 ± 0.12 ; top quartile) and least reactive ($n = 7$; 1.30 ± 0.06 ; bottom quartile) athletes measured during the 10/5 RJT

6.5.3 Principal Component Analysis

The Kaiser-Meyer Olkin measure verified the sampling adequacy for the analysis, $KMO = 0.697$. An initial analysis was run to obtain eigenvalues for each factor in the data. Three factors had eigenvalues over Kaiser's criterion of 1 and in combination, explained 86.1% of the dataset. The scree plot displayed inflections that would justify retaining either 3 or 4 factors. Three factors were retained because of Kaiser's criterion on this value. Table 6.4 details the factor loading after rotation. The items that clustered on the same factor suggest that factor 1 (33.3 % variance) represents sprint times and SSC capabilities; factor 2 (29.9% variance) represents time specific force measures from the ISqT, and factor 3 (22.8% variance) represents absolute and relative strength measures from the ISqT.

Table 6.4 Summary of exploratory principal component analysis results

<i>Rotated Factor Loading</i>			
	1.Sprint times and SSC capabilities	2. Time specific force measures (ISqT)	3. Absolute and relative strength measures (ISqT)
10 – 20 m	.969	.002	.051
20 – 30 m	.967	-.023	.070
5 – 10 m	.872	-.071	-.029
CMJ	-.815	.036	.173
0 – 5 m	.697	-.358	.006
RSI	-.697	.337	.112
Force at 150 ms	-.128	.929	.310
IMP 200 ms	-.175	.926	.301
Force at 100 ms	-.177	.923	.235
Force at 200 ms	-.062	.869	.427
PF	-.042	.318	.941
Maximum Force	-.051	.288	.924
RPF	-.008	.363	.866
Eigenvalues	4.332	3.89	2.70
% variance	33.3	29.9	22.8

CMJ = countermovement jump; IMP = impulse; ISqT = isometric squat; PF = peak force; RPF = relative peak force; RSI = reactive strength index

6.6 Discussion

It was hypothesised that the ISqT, CMJ and RSI would relate to different phases of the 30 m sprint and that each test would distinguish between performance levels of different phases of the sprint, therefore we can accept the hypothesis. There was a moderate relationship between ISqT force at 100 ms and 0 – 5 and 5 – 10 m sprint times. The ISqT was able to distinguish between performance levels over 0 – 5 m, with the athletes who produced the highest forces in 100 ms being significantly faster than those who were in the bottom quartile. These findings are similar to the study by Tillin *et al.* (2013), who reported that force at 100 ms produced during the ISqT had a large relationship to 5 m sprint time but in contrast to the present study also reported this relationship at 20 m. In the present study when the athletes were split into faster and slower groups based upon their 5 m time, the faster group demonstrated a significantly greater ability to produce higher forces during the ISqT. This information details clear relationships between the force produced in the first 100 ms of isometric contraction and early phase acceleration. Results from Fishers r-Z transformation on the relationship between force at 100 ms and 0 – 5 m sprint performance, detailed that there was no significant difference ($p = 0.379$) in the strength of the correlation between the results of Tillin *et al.* (2013) and the present study. The current study performed the ISqT at a knee angle of $138 \pm 5^\circ$, whereas Tillin *et al.* (2013) completed the squats at a knee angle of $118 \pm 5^\circ$. Both studies detailed no relationship between PF (absolute or relative) and sprint performance over any distance. Foot contacts during the acceleration phase are <300 ms (Weyand *et al.* 2000) and it is unlikely that maximal force can be achieved in this time (Aagaard *et al.* 2002), therefore it appears logical that the maximal force achieved in this limited time frame would be related to sprint performance. Further, the players in this study were exceptionally weak ($RPF = 25.0 \pm 5.3$ N/kg). Coaches and practitioners should consider whether these strength levels are adequate for a hurler to possess. They should also consider whether increasing strength levels may lead to improvements in sprint time, with strong relationships observed between the ISqT and 0 – 5 m times in male sprint athletes (Brady *et al.* 2019).

When examining the relationships between time splits and CMJ height, results detailed large or very large correlations with each of the time splits. The correlations strengthened through the sprint phases (0 – 5 m = moderate, 5 – 10 m = large, and 10 – 20 and 20 – 30 m = very large) detailing that the relationship between speed and CMJ height was more related to end phase acceleration. The CMJ was able to distinguish between performance levels at the 10 – 20 m split, with the athletes who jumped higher being faster through this split. The results are similar to those reported in previous research (Wisløff *et al.* 2004, Cronin and Hansen 2005), for example Cronin and Hansen (2005) reported a large correlation between CMJ and 0 – 5 m and this study reported a moderate correlation. When examining the Fisher r - Z transformation between the two r values, no significant difference was observed ($p = 0.342$). The correlations reported between splits from 0 – 10 m and 0 – 30 m were not significantly different ($p = 0.634$ and 0.522 respectively). Further comparison with Wisløff *et al.* (2004), reported no significant difference between correlations measured between CMJ and 0 – 10 m and 0 – 30 m ($p = 0.377$ and 0.704 respectively). This study supports the findings of those studies (Wisløff *et al.* 2004, Cronin and Hansen 2005). As an athlete approaches maximum velocity, strength measures that require force to be produced at high velocities have been reported to be significantly related to sprint performance (Wilson *et al.* 1995, Young *et al.* 1995). A large correlation between force produced in a concentric SJ and 30 m sprint time has been reported ($r = -0.62$) (Wilson *et al.* 1995), however as the velocity of the sprint and distance increase, there is a tendency for the relationships to increase in size throughout the phases. Moderate and large correlations have been reported between CMJ and acceleration from approximately 7 to 18 m from the start line (Nagahara *et al.* 2014). The CMJ and acceleration involves rapid extension and plantarflexion of the three major lower extremity joints, therefore, these comparisons in joint movement could be responsible for the relationship between sprint acceleration ability and CMJ performance.

There were large correlations between the RSI and 5 – 10, 10 – 20 and 20 – 30 m splits. Furthermore, the RSI test was able to distinguish between performance levels at each of these splits. Athletes with high RSI scores were significantly faster through splits except the 0 – 5 m split, however there was

a large effect size reported at this split. The results are similar to other studies that tested RSI using the DJ (Smirniotou *et al.* 2008, Cunningham *et al.* 2016) but are different to the findings of Healy *et al.* (2018) who examined the DJ RSI and RJT method in sprinters and noted that the hopping frequency for the RJT resulted in the test becoming a submaximal test because JH was limited to maintain the prescribed hopping rhythm.

Correlation analysis alone produces some concerns, as it is unclear whether a correlation between any two variables is due to the independent relationship between the two variables, or whether it is coming from another correlated variable. PCA aimed to reduce the dataset whilst retaining as much of the variance as possible and achieved a much greater insight into how strength qualities are associated with each other and with speed. Three well-defined and individual components were identified, explaining 86.1% of the variation in the dataset. Sprint times and SSC capabilities combined accounted for most of the variance (33.3%), followed by time specific force values (29.9%) and finally absolute and relative strength (29.9%) with 13.9% of the variance not explained. These details that SSC, time specific force and absolute strength are separate and distinct qualities, and more importantly, that SSC capabilities are bound into acceleration. This is strengthened by the fact that the strongest correlations were observed between SSC and sprint times, and those athletes with higher RSI score were significantly faster than those with lower scores. This informs us that amongst hurling players, having greater SSC capabilities may strive towards better sprint performance and coaches and practitioners should ensure to include plyometric training of both the fast and slow SSC within their training programme. The separation of time specific force values and absolute and relative strength measures was an important distinction. Since hurling is a non-contact, fast-paced game and maximum acceleration ability is paramount to success, it therefore makes sense that speed and SSC capabilities and having the ability to produce force rapidly were the two largest components identified. Rapid force production is important, as is maximum strength, but these components alone are not enough to ensure rapid acceleration.

Isometric and dynamic muscle contractions provide distinct mechanical and neural conditions for sports performance and the results of this study confirm

an association between both muscle contractions and sprint performance that may have only been assumed previously. The results clearly indicate that force produced in the first 100 ms of isometric contraction relates to early phase acceleration, the CMJ related most strongly to acceleration after 10 m and the RSI relates mostly to acceleration after 5 m. This has important implications for designing training programmes and monitoring muscle function. Since different strength and SSC capabilities are needed for the earlier and later stages of acceleration, training methods for improving specific sprint performance could be selected. Early phase acceleration training should focus on power, and when aiming to improve the middle and later stage of acceleration, therefore coaches should employ training methods with short force production durations such as hopping tasks as well as traditional jumps such as CMJs.

6.7 Conclusion

This study presents a reliable method of assessing isometric multi joint and dynamic jump performance among U21 hurling players. Force measured at 100 ms during the ISqT reported only a moderate relationship with sprint performance, however the test can help in differentiating the fast initial accelerators from the slower ones. The CMJ appears to be most strongly related to late phase acceleration and RSI to nearing maximum velocity. Coaches should understand the different strength-SSC function capabilities required for effective acceleration. PCA can express the complexity of parameters composing speed and strength qualities of hurling players, which represent the dominance of speed and SSC capabilities, rapid force production and maximum strength.

Chapter 7: Summary, Conclusion and Recommendation

7.1 Summary

The aim of this thesis was to determine and compare the reliability of the IMTP and ISqT and investigate the relationship between isometric strength and sprint performance in track and field sprinters and field sport athletes. To address the specific aims, the thesis was divided into five distinct but inter-related studies comprising of a narrative review (Study 1) and four cross-sectional studies (Study 2, 3, 4 & 5). No studies were conducted in their respective areas with the population cohorts used. No study examined the reliability and compared the IMTP and ISqT at the same knee and hip angle among a group of athletes from different sporting background. No study examined the relationship between isometric strength and sprint performance among a group of sprinters where the force-time curve was fully diagnosed and the 0 – 5 m time split was included in analysis. No previous research examined the relationship of isometric strength to sprinting kinematics among sprinters and finally no previous study had examined the relationship of isometric strength and sprint performance among hurling players.

Similar IMTP and/or ISqT variables were reliable across studies 2, 3, 4 & 5. In all studies, no time specific variables < 100 ms were deemed reliable. This may be due to the training background of the athletes involved and/or the fact that only one familiarisation session was performed. A number of variables deemed unreliable in study 2 were deemed reliable in studies 3, 4 & 5. The reason for this may be because the athletes in study 2 were from various training backgrounds and different sports, compared to studies 3, 4 & 5 where athletes were from similar training backgrounds and the same sport.

The relationship of isometric strength to sprint performance was examined among male sprinters, female sprinters and hurling players. Results detail different strength correlations for each of these cohorts. For example, ISqT RPF very largely correlated to 0 – 5 m time ($r = -0.714$) among male sprinters. This relationship was weaker among females with a moderate relationship ($r = -0.410$) observed and lessened further among the hurling group to a small relationship ($r = -0.212$). On examination of strength levels, there was no significant difference between the male and female sprinters ISqT RPF scores (males = $30.6 \pm$ N/kg, females = 29.2 ± 7.4 N/kg). The male hurlers' scores

were lower than both the male and female sprinters (25.0 ± 5.3 N/kg). The low levels of strength could explain the lack of relationship observed among the male hurlers. With the athletes being considered weak, they may not have high enough strength levels, and coaches may consider aiming to increase hurling players strength levels to determine whether this relationship to sprint performance exists if the athletes become stronger. However, this does not explain the relationship observed with the female sprinters. On further comparison of force at 100 ms and IMP 0 – 200 ms, the female sprinters and male hurlers had similar scores. The female sprinters produced 897 ± 347 N in the first 100 ms of the ISqT with the hurlers producing 856 ± 243 N. By comparison, the male sprinters produced 1193 ± 446 N. A similar pattern was observed with IMP 0 – 200 ms, the female sprinters producing 173 ± 6.3 N.s, similar to the hurlers producing 856 ± 243 N.s, with the male sprinters much higher at 225 ± 51 N.s. Since sprinting is limited to force production in short time frames (foot contacts = 100 – 200 ms) and the stronger relationships are observed with sprinters who produce higher force in the early time periods, coaches and practitioners should include exercises which support this rapid force production. This is possibly more important for those training hurlers and female sprinters, who in this study, showed low levels of rapid force production.

The acceleration of a body is directly proportional to the net force acting on the body, in the direction of the net force, and is inversely proportional to the mass of the body. The IMP produced is equal to the momentum outcome of the movement, for example at the start of sprinting. Therefore, any changes in forces produced will affect the momentum of the body in the desired direction. With the limited time periods available over which force can be applied, IMP produced in short time-periods is paramount to athletic success. This has been observed in the strong relationships between 0 – 5 m sprint time and IMP 0 – 200 ms, where athletes who produce a large IMP are quicker over the first 5 m. This was detailed further in study 4, where athletes who produced a large IMP had a long rear block clearance step length, which resulted in a higher velocity and a faster time over 0 – 5 m. This IMP-momentum relationship plays an important role in sports performance, and

coaches and practitioners should ensure that where possible IMP is measured and its application to performance is considered.

Study 1 reviewed the reliability of the IMTP and ISqT and the reporting of normative data. This review was warranted, due to the conflicting reports of some variables in the literature with the reporting of literature not standardised across the research. Several studies only report the ICC as its reliability measure with very few studies reporting the CV and CIs leaving the level of reliability unknown in these studies. PF is the most reliable measure reported in the literature and can be used to determine an athlete's maximum strength capabilities. The review identified that while there is a substantial amount of literature on the reliability on the IMTP, research on the reliability of the ISqT is far more limited. One study had compared RPF in male NCAA Division 1 American football players and track and field athletes and determined that 12.5% additional force was produced during an ISqT when compared to the IMTP. The authors did not examine additional measures such as RFD and IMP. In addition, the review identified that there is limited research using female athletes. Therefore, the next study (Study 2) in this thesis collected data on male and female athletes completing both the IMTP and ISqT and compared the results of both tests.

Study 2 examined the reliability and usefulness of the IMTP and ISqT performed at the same knee and hip angles and compared the scores produced in each test to determine the magnitude of difference between tests. The main findings of this study suggested that measures of maximum force, absolute PF, RPF, RFD (0 – 200 ms and 0 – 250 ms) and IMP (0 – 300 ms) are reliable in both tests with additional measures of IMP reliable in the ISqT. All short sampling windows of RFD (up to 150 ms), pRFD (up to 50 ms), IMP (0 – 100 ms), IES, RC, S-gradient and A-gradient were deemed unreliable for both tests. Both tests were able to detect the SWC for PF values. Female athletes produced significantly higher PF and RPF during the ISqT compared to the IMTP. The ISqT may be the preferred test for female athletes when examining maximum lower extremity strength. Having determined the level of reliability of both tests and identifying that females produce more force during the ISqT compared to the IMTP, the next study (Study 3) in this thesis investigated the

relationship of both the IMTP and ISqT and sprint performance in track and field sprinters.

Study 3 investigated the relationship between the IMTP and ISqT and sprint performance in track and field sprinters and determined whether differences existed between males and females. Among the groups, additional variables were reliable compared to Study 2, possibly due to the athletes being from the same training background compared with Study 2 where athletes were from different sports. Results detailed that among male sprinters, IMTP and ISqT measures largely correlated with 0 – 5 m time; athletes producing higher force values were faster over the first 5 m. There was no relationship observed with the female sprinters. The study highlighted that the 0 – 5 m section of acceleration is an important component of the race as it very largely correlated with the outcome (30 m sprint time). It details the importance of recording the 0 – 5 m split and that the physical demands of acceleration change throughout the phases with isometric strength accounting for 33 - 37% of the variance in male sprinters 0 – 5 m performance. Having determined this relationship among male sprinters, the next study in this thesis (Study 4) investigated the relationship between the IMTP and sprint kinematics in the first 5 m. With no relationship observed among female sprinters, the female data was not analysed for Study 4.

Study 4 examined whether the IMTP variables reported to relate to 0 – 5 m sprint time among male sprinters had any meaningful relationship with sprint kinematics from the blocks and over the first 5 m. The main findings identified that higher force production resulted in higher velocities leaving the blocks, at step 2 and resulted in longer relative step lengths at block clearance. The study identified that some athletes were using a suboptimal technique and may have been unable to express their strength effectively and this may have explained some of the results observed. Having established the relationship between isometric strength and sprint performance among track and field sprinters, Study 5 aimed to examine the relationship between the ISqT and hurling players.

Study 5 examined the relationship between the ISqT, CMJ and RSI and sprint performance in hurling players. Due to time constraints there was only enough

time to carry out one isometric test among this cohort. After a consultation with the hurling teams S&C coach, I decided that the ISqT would be the preferred test, as this was more related to the players training background and there was a lack of research using the ISqT among field sports athletes. Previous research has identified moderate and large correlations between the CMJ and RSI and sprint performance among track and field sprinters, rugby and soccer players. No previous research had examined this relationship among hurling players. Therefore, for this study, I decided to have the players perform the CMJ and 10/5 RJT along with the ISqT to give a greater overall depiction of the strength and power qualities of hurling players, and determine how these qualities relate to sprint performance. The key findings of this study were that force at 100 ms correlated with 0 – 5 m and 5 – 10 m sprint times, CMJ correlated with all splits and RSI correlated with splits over 5 m. Further, force at 100 ms distinguished between performance levels from 0 – 5 m, CMJ from 10 – 20 m and RSI from 20 – 30 m; the faster athletes produced significantly higher force, JHs and RSI scores. The additional PCA analysis identified that three PCs explain 86.1% of the variance in the dataset, with sprint times and SSC capabilities accounting for 33.3%, time specific force values accounting for 29.9% and absolute and relative strength accounting for 22.8%.

7.2 Conclusion

This thesis has contributed several novel findings to the current literature on isometric strength testing and the relationship between isometric strength and sprint performance. The specific conclusions that can be drawn from the five studies are as follows:

- PF is the most reliable measure and can be used to determine an athlete's maximum strength capabilities (Study 1, Chapter 2).
- Similar measures are reliable in both the IMTP and ISqT and the measure of PF is capable of detecting changes in performance. Female athletes produce significantly greater PF during the ISqT, with no significant differences among male participants (Study 2, Chapter 3).

- All short sampling windows of RFD (up to 1050 ms), pRFD (up to 50 ms), IMP (0 – 100 ms), IES, RC, S-gradient and A-gradient were deemed unreliable for both tests (Study 2, Chapter 3).
- Among males, PF, force at 100, 150 and 200 ms, RFD (0 – 150 and 0 – 200 ms) and IMP (0 – 200 ms) measured during the IMTP and ISqT largely and very largely correlate to 0 – 5 m sprint performance. Isometric strength can have a sizable influence on 0 – 5 m time, but in some cases the maximum effect could be very small (Study 3, Chapter 4).
- Higher force generation in the IMTP is related to faster velocities at rear block clearance and step 2 and longer rear block clearance relative step length among male sprint athletes (Study 4, Chapter 5).
- Force at 100 ms measured during the ISqT relates to 0 – 5 m and 5 – 10 m sprint performance in hurling players. CMJ height relates to all splits up to 30 m and RSI relates to splits over 5 m. PCA identified that sprint times and SSC capabilities account for 33.3% of the variation in the dataset with time specific force values accounting for 29.9% and absolute and relative strength accounting for 22.8% (Study 5, Chapter 6).

7.3 Limitations

The limitations of the thesis as a whole are provided below:

- ***Population specificity of results:*** Study 2 was conducted on 26 male and female Irish athletes from different sports who competed at National and International level in their respective sports. Studies 3 and 4 were conducted on Irish track and field sprinters (n = 25 and n = 15 respectively) competing at National and International level and Study 5 was conducted on an U21 Irish hurling team (n = 26). Therefore, the results are specific to an Irish context amongst different sporting backgrounds.

- ***Sprinting technique:*** The authors had no control over the sprinting techniques used by the participants in the studies included in this thesis. Therefore, several athletes may have been utilising poor technique, resulting in poor sprint performance. All participants had taken part in sprint acceleration technique training, including the hurling players but it is unknown whether optimal technique was used and whether improved technique alone would improve sprint times.
- ***Lack of longitudinal data:*** While large relationships between isometric strength and sprint performance were observed in this thesis, it is unknown if increases in isometric strength measures will transfer to improvements in speed time as studies 3, 4, 5 & 6 were cross sectional studies. A longitudinal study would identify if changes in measures of isometric strength had any effect on sprint performance.
- ***Lack of female participants in studies 4 and 5:*** The relationship between isometric strength and sprint kinematics has not been examined and should be considered for future research. In addition, a female team sport should be recruited to participate in a study similar to Study 5 completed among the male hurling group. It is unknown what relationship exists between isometric strength and sprint performance among female team sport athletes.

7.4 Practical Applications

Based on the findings from this research, several practical applications for the use of isometric strength testing and how it relates to sprint performance in track and field sprinters and hurling players can be applied including:

- Isometric strength tests are useful as they are time efficient, especially with large groups and compared with dynamic strength testing; the IMTP/ISqT may provide a truer measure of maximum strength. Coaches should monitor isometric, dynamic and reactive strength capabilities of athletes to ensure that the optimal training stimulus is provided in order to enhance the specific strength qualities of the athlete to increase performance.

- Coaches need to ensure the optimal position is used for the IMTP, with a knee angle of 130-140° with an upright torso. The analysis methods of the force-time curve must be clearly understood for true comparison of research.
- There is a lack of reliability studies using both reliability criteria at a higher level ($ICC \geq 0.80$ and a $CV \leq 10\%$) and coaches must be aware of this when selecting the measure, they want to report. Measures such as RFD and IMP have been reported to be reliable in previous research, however there are conflicting reports of this in the literature. Limitations exist with isometric testing and coaches should always perform in house reliability testing, calculating ICCs, CVs and CIs.
- The IMTP and ISqT are reliable for maximum force, absolute PF, RPF, RFD (0 – 200 ms and 0 – 250 ms) and IMP (0 – 300 ms). IMP (0 – 200 ms and 0 – 250 ms) is reliable in the ISqT.
- A number of variables were deemed unreliable in both tests. Coaches and practitioners should avoid using these unreliable variables, as the precision of single measurements would be poor and the ability to track changes in performance would be limited leaving them inadequate.
- PF is the most reliable measure and can be used to determine an athlete's maximum strength capabilities and can detect meaningful change in both tests ($SWC_{0.2}$). Where the TE is above the $SWC_{0.2}$, coaches and practitioners can use $SWC_{0.5}$ to provide context of “*meaningful change*” for all other variables in both tests. If the test is not highly reliable ($ICC \geq 0.8$ & $CV \leq 10\%$), then it is not appropriate to evaluate the effect of training programmes.
- Significant differences exist between the IMTP and ISqT for measures of absolute PF, RPF, AlloPF and IMP (0 – 300 ms). If coaches and practitioners are looking to measure an athlete's true maximum strength, the ISqT may be the preferred test, especially among female athletes.
- Variables measured in the IMTP and ISqT are largely correlated with 0 – 5 m sprint performance in male sprinters. Practitioners and

researchers are advised to use split times including the 0 – 5 m split along with an outcome measure when investigating correlations because sprinting is a skill requiring high technical and physical demands and these change throughout the sprint phases. Practitioners should consider that isometric strength measures account for 33 – 37% of the variance in 0 – 5 m performance.

- Athletes that produce higher measures of PF and time specific force values had higher modified rear block clearance velocity, velocity of step 2 and a longer rear block clearance step length. There is an underlying strength quality associated with step length, and if increasing step length is a technical goal, maximal strength training could be considered as an additional training method.
- The ISqT is a reliable test to use among hurling players. Force at 100ms in the ISqT can differentiate fast initial accelerators from slower ones. The PCA explained the complexity of parameters composing speed and strength qualities of hurling players, which represent the dominance of speed and SSC capabilities, rapid force production and maximum strength and all areas should be considered within their training programme.

7.5 Future Recommendations

The conclusions from this thesis have added to the understanding of the reliability of isometric strength testing and the relationship of isometric strength to sprint performance among track and field sprinters and hurling players. However, there remains unanswered questions within the current scientific literature, with specific recommendations of this thesis as a whole provided below:

- There is a need to determine if different knee and hip angles in the ISqT produced higher forces than those used in this study.
- Further, the relationship between force produced at these different knee angles relate to sprint performance from the blocks, such as utilising a

90° and 120° knee angle, which replicate the front and back knee angles in the set position in the blocks (Mann and Murphy 2015).

- More research is needed to determine the reasons behind the relationship between isometric strength and sprint performance not being observed not among female sprinters.
- While the results of this thesis demonstrated that isometric strength measures account for 33 – 37% of the variance in the 0 – 5 m performance, it is unknown if increases in isometric strength will transfer to reductions in sprint time. Further investigations should aim to examine the effects of increased levels of isometric strength, achieved through dynamic training methods, on changes in sprint times in both track and field sprinters and team sport athletes.
- This thesis had no influence on sprinters technique from the blocks and identified some athletes that used a suboptimal technique. Further research should aim to identify whether changes in block settings or coaching techniques used to clear the blocks result in changes in the way athletes are able to express their strength.
- Future research should use instrumented blocks to examine the relationship between measures of isometric strength and force exerted on the blocks when leaving the blocks. This would also allow for measurement of true block clearance time and velocity compared to the modified versions used in this study.

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Chapter 9: Appendices

Appendix 1: Participant Information Sheets



UNIVERSITY of LIMERICK

OLLSCOIL LUIMNIGH

Participant Information Sheet

Please read the information below thoroughly before deciding whether or not to participate in this project.

Introduction

You have been invited to participate in a project investigating “*The reliability of the isometric strength testing*”. The project is being carried out by PhD student Claire Brady (University of Limerick).

Aim of the project

The aim of this research is to determine the reliability of the isometric mid-thigh clean pull. The research using force platforms will analyse the reliability of data collected from two separate testing sessions. The research will specifically analyse the amount of force generated (peak force) and the rate at which this force can be exerted (rate of force development). The isometric mid-thigh clean pull is used to determine the strength and power profile of athletes to help plan interventions to target athlete’s individual needs to improve performance and reduce injury risk. By analysing these variables, the researcher aims to determine if the variables are reliable and can therefore inform coaches of athlete’s strength and power levels.

Procedure

You will be asked to participate in a study assessing an athlete’s strength and power profile. The testing will measure performance variables using equipment such as a Sorinex isometric testing system with an integrated Kistler force plate. This procedure will be carried out at the Irish Institute of Sport. There is no major risk involved in this procedure from using the force platform. The participant will undertake a specific warm up and a warm up of sub-maximal isometric mid-thigh clean pulls followed by the testing session which will consist of three maximal isometric mid-thigh clean pull with 2 minutes between efforts. Each pull will last 3-4 seconds. Athletes will complete this protocol on

two separate testing sessions. Participants will be engaged in activities in the study which are familiar to them and not beyond anything that they do in their normal training regimes.

Benefits

Strength and power are critical components of an athlete's performance. From the results of strength and power testing an athlete's strengths and weaknesses can be identified. The subsequent planned programme should address the athlete's weaknesses so as to optimise the effectiveness of the programme to enhance sporting performance. This bespoke strength and power diagnostic system will also be used for preventing injury, reducing the incidence of illness, guiding rehabilitation and enhancing athletic welfare and performance.

Confidentiality

This project has been approved by the Education and Health Sciences Research Ethics Committee in the University of Limerick. All information gathered in this project will remain completely anonymous and strictly confidential. All testing protocol will be identified using a code number and your name will not be recorded or used in any part of this project. In the event data are used for publication anonymity of individuals will be upheld. All data will be stored in a locked filing cabinet in the principal researcher's office.

Withdrawing from the project

Participation in this project is completely voluntary. You have the right to withdraw from the project at any time without any penalty.

If you would like to participate in this project or if you require further information please contact:

Claire Brady, University of Limerick, email: claire.brady@ul.ie
Tom Comyns, University of Limerick, email: tom.comyns@ul.ie

This research study has received Ethics approval from the Education and Health Sciences Research Ethics Committee (2016_03_02_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



UNIVERSITY of LIMERICK

OLLSCOIL LUIMNIGH

Participant Information Sheet

Please read the information below thoroughly before deciding whether or not to participate in this project.

Introduction

You have been invited to participate in a project investigating “*Strength and power profiles of various athletic population groups*”. The project is being carried out by PhD student Claire Brady (University of Limerick).

Aim of the project

The aim of this research is to compare the strength and power profiles of explosive, endurance and Paralympic athletes. The research using force plates will analyse the strength and power profiles of athletes from a range of different sports. This will involve two testing sessions. The first testing session will specifically analyse the amount of force generated (peak force) and the rate at which this force can be exerted (rate of force development) during an isometric mid-thigh clean pull. The second session will involve a testing day where a number of jumps will be tested to include countermovement jump, squat jump, drop jumps from various heights and single and double leg standing long jumps. The results will provide strength and power profiles of development and senior speed, endurance and Paralympic athletes. This will provide information that can help with identifying an athlete’s strengths and weaknesses and ultimately help plan interventions to target athlete’s individual needs to improve performance and reduce injury risk.

Procedure

You will be asked to participate in a study assessing an athlete’s strength and power profile. The testing will measure performance variables using equipment such as a Sorinex isometric testing system with an integrated Kistler force plate. This procedure

will be carried out at the Irish Institute of Sport. There is no major risk involved in this procedure from using the force platform. The participant will undertake a specific warm up and a warm up of sub-maximal isometric mid-thigh clean pulls followed by the testing session which will consist of three maximal isometric mid-thigh clean pull with 2 minutes between efforts. Each pull will last 3-4 seconds. On a separate testing session participants will complete a series of jump tests. After a specific warm up, participants will complete three repetitions of a series of jumps (countermovement jump, squat jump, drop jumps from various heights and single and double leg standing long jumps). A minimum of one-minute rest will be given between jumps. Participants will be engaged in activities in the study which are familiar to them and not beyond anything that they do in their normal training regimes.

Benefits

Strength and power are critical components of an athlete's performance. From the results of strength and power testing an athlete's strengths and weaknesses can be identified. The subsequent planned programme should address the athlete's weaknesses so as to optimise the effectiveness of the programme to enhance sporting performance. This bespoke strength and power diagnostic system will also be used for preventing injury, reducing the incidence of illness, guiding rehabilitation and enhancing athletic welfare and performance.

Confidentiality

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UNIVERSITY of LIMERICK

OLLSCOIL LUIMNIGH

Participant Information Sheet

Please read the information below thoroughly before deciding whether or not to participate in this project.

Introduction

You have been invited to participate in a project investigating “*An evaluation of the correlation between an athlete’s strength and power profile and performance indicators*”. The project is being carried out by PhD student Claire Brady (University of Limerick).

Aim of the project

The aim of this research is to determine if there is a relationship between an athlete’s strength and power profile and key performance indicators of their sport. The isometric mid-thigh clean pull will be used to determine the strength and power profiles of the athletes. Key performance indicator tests used will include countermovement jump, standing long jump and 10m acceleration. The strength and power dependant variables that are related to enhancing sporting performance will be identified. This will assist with programme design and in coaches addressing strength and power areas that will have a direct enhancement on performance.

Procedure

You will be asked to participate in a study assessing an athlete’s strength and power profile and the key performance indicators for your sport. The testing will measure performance variables using equipment such as a Sorinex isometric testing system with an integrated Kistler force plate. This procedure will be carried out at the Irish Institute of Sport. There is no major risk involved in this procedure from using the force platform. The participant will undertake a specific warm up and a warm up of sub-maximal isometric mid-thigh clean pulls followed by the testing session which will consist of three

maximal isometric mid-thigh clean pull with 2 minutes between efforts. Each pull will last 3-4 seconds. Athletes will then participate in a testing session specific to their sport. This includes but is not limited to countermovement jump, standing long jump, drop jump, 10m/30m acceleration, VO2max and running economy. Participants will be engaged in activities in the study which are familiar to them and not beyond anything that they do in their normal training regimes.

Benefits

Strength and power are critical components of an athlete's performance. From the results of strength and power testing an athlete's strengths and weaknesses can be identified. The subsequent planned programme should address the athlete's weaknesses so as to optimise the effectiveness of the programme to enhance sporting performance. This bespoke strength and power diagnostic system will also be used for preventing injury, reducing the incidence of illness, guiding rehabilitation and enhancing athletic welfare and performance.

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This project has been approved by the Education and Health Sciences Research Ethics Committee in the University of Limerick. All information gathered in this project will remain completely anonymous and strictly confidential. All testing protocol will be identified using a code number and your name will not be recorded or used in any part of this project. In the event data are used for publication anonymity of individuals will be upheld. All data will be stored in a locked filing cabinet in the researcher's office.

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Appendix 2: Informed Consent Forms



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O L L S C O I L L U I M N I G H

Participant Consent Form

“The reliability of the isometric strength testing”

- I have read and fully understand the participant information sheet.
- I understand what the project is about and what the results will be used for.
- I am fully aware of all procedures involving myself and of any risks and benefits associated with the project.
- I know that my participation is voluntary and that I can withdraw from the project at any stage without giving any reason.

I the undersigned have been fully informed of and understand the nature of this project. I am aware of the risks involved and agree to be a participant in this project.

Signature of Participant: _____

Date: _____

Printed name: _____

Signature of Researcher: _____

Date: _____

Printed name: _____

This research study has received Ethics approval from the Education and Health Sciences Research Ethics Committee (2016_03_02_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*



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OLLSCOIL LUIMNIGH

Participant Consent Form

“Strength and power profiles of various athletic population groups”

- I have read and fully understand the participant information sheet.
- I understand what the project is about and what the results will be used for.
- I am fully aware of all procedures involving myself and of any risks and benefits associated with the project.
- I know that my participation is voluntary and that I can withdraw from the project at any stage without giving any reason.

I the undersigned have been fully informed of and understand the nature of this project. I am aware of the risks involved and agree to be a participant in this project.

Signature of Participant: _____

Date: _____

Printed name: _____

Signature of Researcher: _____

Date: _____

Printed name: _____

This research study has received Ethics approval from the Education and Health Sciences Research Ethics Committee (2016_03_02_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*



UNIVERSITY of LIMERICK

O L L S C O I L L U I M N I G H

Participant Consent Form

“An evaluation of the correlation between an athlete’s strength and power profile and performance indicators”

- I have read and fully understand the participant information sheet.
- I understand what the project is about and what the results will be used for.
- I am fully aware of all procedures involving myself and of any risks and benefits associated with the project.
- I know that my participation is voluntary and that I can withdraw from the project at any stage without giving any reason.

I the undersigned have been fully informed of and understand the nature of this project. I am aware of the risks involved and agree to be a participant in this project.

Signature of Participant: _____

Date: _____

Printed name: _____

Signature of Researcher: _____

Date: _____

Printed name: _____

This research study has received Ethics approval from the Education and Health Sciences Research Ethics Committee (2016_03_02_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*

Appendix 3: Published Journal Article and Conference Presentations



A review of the reliability of biomechanical variables produced during the isometric mid-thigh pull and isometric squat and the reporting of normative data

Claire J. Brady^{a,b} , Andrew J. Harrison^a  and Thomas M. Comyns^a

^aFaculty of Education and Sport Sciences, Biomechanics Research Unit, Department of Physical Education & Sports Sciences, University of Limerick, Limerick, Ireland; ^bSport Ireland Institute, National Sports Campus, Dublin, Ireland

ABSTRACT

The use of isometric strength testing, particularly the isometric mid-thigh pull (IMTP) has increased dramatically over the last decade. The IMTP and isometric squat (ISqT) provide one aspect of performance monitoring with variables such as peak force and rate of force development being derived from the force–time curve. The reliability of some of these variables is conflicting in the literature, and the reporting of the reliability is not standardised across the research. The majority of research only reports intraclass correlation coefficients with very few studies reporting coefficient of variation and 90% confidence intervals. Additionally, methods used to calculate variables from the force–time curve differ across studies. An aim of muscle strength testing is to provide normative values for specific sports, allowing coaches to distinguish between performance levels or evaluate the effects of training on performance. This narrative review aims to evaluate studies that have researched the reliability and/or reported normative data for both tests. Additionally, the testing protocols and the force–time curve analysis techniques utilised are discussed, concluding with practical applications for coaches on the uses and limitations of these tests. Results demonstrate that peak force is the most reliable measure and can be used to determine maximum strength capabilities.

ARTICLE HISTORY

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KEYWORDS

Peak force; rate of force development; impulse; force–time curve; athlete profiling

Introduction

Strength can be defined as the ability to produce force against a resistance (Stone, 1993). Maximal force generating capabilities are commonly monitored in athletes and can be evaluated using dynamic or isometric muscle contractions (Beckham et al., 2013; Hafl et al., 2005). According to Juneja, Verma, and Khanna (2010) the isometric mid-thigh pull (IMTP) appears to be the most commonly used isometric assessment when attempting to evaluate the force–time curves of athletic populations. Isometric tests such as the IMTP or isometric squat (ISqT) may be preferred to dynamic tests such as the 1 repetition maximum

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A Comparison of the Isometric Mid-Thigh Pull and Isometric Squat: Intraday Reliability, Usefulness, and the Magnitude of Difference Between Tests

Claire J. Brady, Andrew J. Harrison, Eamonn P. Flanagan, G. Gregory Haff,
and Thomas M. Comyns

Purpose: This investigation examined the reliability and usefulness of the isometric mid-thigh pull (IMTP) and isometric squat (ISqT) performed at the same knee and hip angles. The scores produced in each test were compared to determine the magnitude of differences between tests. **Methods:** Twenty-six male and female athletes (age, 23.6 [4.3] y; height, 1.75 [0.07] m; and body mass, 68.8 [9.7] kg) performed 2 maximal repetitions of the IMTP and ISqT following a specific warm-up. **Results:** Maximum force, absolute peak force (PF), relative PF, allometrically scaled PF, rate of force development (0–200 and 0–250 ms), and impulse (0–300 ms) were deemed reliable (intraclass correlation coefficient ≥ 0.86 and coefficient of variation $\leq 9.4\%$) in the IMTP and ISqT based on predetermined criteria (intraclass correlation coefficient ≥ 0.8 and coefficient of variation $\leq 10\%$). Impulse (0–200 and 0–250 ms) was reliable in the ISqT (intraclass correlation coefficient ≥ 0.92 and coefficient of variation $\leq 9.9\%$). Participants produced significantly ($P < .05$) greater PF and impulse (0–300 ms) during the ISqT compared with the IMTP. When split by sex, female participants produced significantly greater PF ($P = .042$) during the ISqT, with no significant differences among male participants ($P = .245$). Both tests are capable of detecting changes in performance in maximum force and absolute PF. **Conclusions:** Both tests are reliable for short time-dependent maximal strength measures when measured at the same knee and hip angles. The ISqT may be preferred when coaches want to test an athlete's true maximum lower limb strength, especially female athletes.

Keywords: isometric strength, force-time curve, maximum strength, explosive strength, performance testing

Isometric tests such as the isometric mid-thigh pull (IMTP) and isometric squat (ISqT) allow the assessment of athletes' strength qualities from a force-time curve and are used to assess skeletal muscle function.^{1,2} Buckner et al.³ suggested that typical strength assessments such as 1-repetition maximum testing are skills and that using multiple measures such as the IMTP or ISqT may be more advantageous for defining true measures and changes in strength. The IMTP is designed to replicate the body position at the beginning of the second pull position of the clean or snatch.¹ The second pull position (130°–140° knee angle with an upright trunk position¹) is the strongest and most powerful position during weightlifting movements, generating the highest forces and velocities of any part of the lift.⁴ From the force-time curve produced in these tests, there are a number of variables that can be examined. Peak force (PF, maximum force produced) is indicative of "maximum strength," and rate of force development (RFD) is indicative of an athlete's ability to produce maximal force in minimal time.⁵ To describe different portions of the force-time curve, Zatsiorsky⁶ calculated the index of explosiveness (IES), reactivity coefficient (RC), S-gradient, and A-gradient. The IES refers to the ability to exert maximal forces in minimal time, and the RC expresses the IES relative to body weight.⁶ The S-gradient quantifies RFD at the beginning of muscular effort, whereas the A-gradient characterizes RFD in the late stages.⁶ Although Haff et al.⁸ have applied these to

the force-time curve of an IMTP, they have not yet been applied to the ISqT. Impulse determines the change in momentum of an athlete and is an important performance-related characteristic.

With the increased popularity of isometric tests being used to assess strength qualities, it is important that the data obtained to prescribe, monitor, and alter an athlete's training program are reliable. Superior reliability results in better precision of single measurements and enhanced tracking of changes in measurement in both research and practical settings.⁹ To assess test-retest reliability, it is recommended that the intraclass correlation coefficient (ICC) and the typical error (TE) expressed as a coefficient of variation (CV) should be calculated¹⁰ along with 95% confidence intervals.⁶ Although there are no predetermined standards set for measurements of reliability in sports science, the literature has commonly used a threshold of an ICC ≥ 0.8 and a CV $\leq 10\%$.⁹

Early research on the IMTP only reported the ICC as the reliability measure and reported PF and peak RFD (pRFD) as reliable.^{1,10–12} PF is by far the most reliable variable, with an ICC ≥ 0.92 and a CV $\leq 5\%$ reported in the literature.^{8,10–12} Research on the reliability of the ISqT is limited compared with the IMTP, but generally results in PF being the most reliable variable, with tests performed at various knee angles (ICC ≥ 0.97).^{10,16–18} Variables including RFD and impulse have been reported as reliable in the IMTP^{8,10–12} and ISqT.¹⁷ There are different methods for calculating the RFD, including preset time bands,^{13,19} determining the pRFD across various windows,^{13,19,20} and using the slope of the curve from the initial rise to the maximum force expression (average RFD, avgRFD).^{8,21} Haff et al.⁸ found that using selected time bands for the quantification of the RFD offers greater reliability compared with the quantification of the pRFDs. AvgRFD⁸ has

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The Relationship Between Isometric Strength and Sprint Acceleration in Sprinters

Claire J. Brady, Andrew J. Harrison, Eamonn P. Flanagan, G. Gregory Haff, and Thomas M. Comyns

Purpose: To examine the relationships between isometric mid-thigh pull (IMTP), isometric squat (ISqT), and sprint acceleration performance in track-and-field sprinters and to determine whether there are differences between males and females. **Methods:** Fifteen male and 10 female sprinters performed 3 maximal-effort IMTPs, ISqTs, and 3 × 30-m sprints from blocks. **Results:** Among males, the results showed significant negative correlations between IMTP and ISqT peak force, relative peak force, force at 100, 150, and 200 ms, rate of force development (0–150 and 0–200 ms), and impulse (0–200 ms) and 0- to 5-m time ($r = -.517$ to $-.714$; $P < .05$). IMTP impulse ($B = -0.582$, $P = .023$) and ISqT relative peak force ($B = -0.606$, $P = .017$) significantly predicted 0- to 5-m time. Among females, no IMTP or ISqT variables significantly correlated with any sprint times. Males measured significantly higher than females for all IMTP measures except for relative peak force. Males were significantly faster than females at all splits. When comparing measures of the ISqT, there were no significant differences between males and females. **Conclusion:** Variables measured during the IMTP and ISqT significantly correlated with 0- to 5-m sprint performance in male athletes. Isometric strength can have a sizable influence on 0- to 5-m time, but in some cases, the maximum effect could be very small.

Keywords: force–time curve, performance testing

Successful performance in sprint events requires rapid acceleration and a high maximum velocity. The starting block phase and the subsequent acceleration phase are important phases, which directly generate the results in 60- and 100-m sprints.¹ During the acceleration phase, an athlete's expression of strength will change; for example, lower-limb power measured during squat jumps and countermovement jumps significantly correlate with acceleration from the fifth to 11th steps, and reactive strength measured through repeat ankle jumps significantly correlate with acceleration from the 14th to 19th steps.² Regarding the sprint start, Slawinski et al³ concluded that sprinters with greater "explosive strength" were able to generate a greater rate of force development (RFD) and impulse, and, thus, a greater velocity from the starting blocks to the toe-off of the second step. Therefore, a sprinter's absolute strength and ability to express forces rapidly are key features of their ability to accelerate efficiently. In addition, the mechanical outputs of world-class sprinters during the acceleration phase are greater in males than in females; females also have a shorter acceleration phase. Therefore, these strength qualities could be different between males and females.⁴

Maximum strength has been defined as the ability to produce maximum force against an external resistance.⁴ The isometric mid-thigh pull (IMTP) and isometric squat (ISqT) are 2 tests commonly used to test an athlete's maximum strength capabilities, and these tests can measure variables such as peak force, RFD, and impulse.⁵ The relationship between maximum strength measured during the IMTP/ISqT and sprint performance has been examined among male soccer and rugby players.^{6–8} There appear to be significant negative correlations between IMTP peak force and sprint times over 5 m

($r = -.57$) and 20 m ($r = -.69$) among collegiate male soccer and rugby league players.⁹ Furthermore, significant negative correlations ($r = -.5$ to $-.7$) have been found between peak RFD (pRFD) and sprint times over 5,^{9,10} and 20 m⁹ among soccer and rugby players. In addition, Wang et al⁶ reported a significant ($P < .05$) negative correlation between sprint time over 5 m and RFD from 0 to 30 ms ($r = -.57$) and RFD from 0 to 30 ms ($r = -.53$). Among a group of athletes from various sports, Conlon et al¹⁰ reported that IMTP peak force and pRFD correlated with 5-m ($r = -.58$ and $-.49$, respectively), 10-m ($r = -.61$ and $-.5$, respectively), 20-m ($r = -.61$ and $-.47$, respectively), and 30-m sprint times ($r = -.61$ and $-.46$, respectively). Tillin et al⁸ is the only study, to the authors' knowledge, that has examined the relationship between ISqT force measures and sprint times among rugby players. The results showed that sprint times were related to early phase ISqT force (5100 ms) normalized to maximal force (ie, expressed as a percentage of maximal force; 5 m, $r = -.63$, $P = .005$, and 20 m, $r = -.54$, $P = .002$).

Although negative correlations between isometric force production and sprint performance have been found, sprinters differ from field-sport athletes in their start position. Field-sport athletes start from various positions, such as rolling or jogging starts, whereas sprinters start their race from starting blocks, which require a high technical ability in order to apply optimum vertical and horizontal force.¹ Wild et al¹¹ compared sprinters' and rugby players' acceleration techniques and showed that there were multiple differences in the magnitudes of various touchdowns and toe-off kinematics between the 2 groups. It is difficult to assess sport-specific variables among a group of sprint athletes, because subjects generally end up being either a large heterogeneous group¹⁰ (139 male and female athletes were recruited from various sports, including track and field, soccer, gymnastics, etc) or smaller, more homogeneous groups¹² (5 male and female elite sprinters). Recently, Healy et al¹³ found no significant relationships between IMTP peak force and relative peak force and sprint performance over 40 m with 10-m splits among a group of 28

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COMPARISON OF THE RELIABILITY OF PEAK FORCE MEASURED DURING AN ISOMETRIC MID-THIGH PULL AND ISOMETRIC SQUAT.

Claire J. Brady, Andrew J. Harrison, Eamonn P. Flanagan, and Thomas M. Comyns.

Biomechanics Research Unit, University of Limerick, Limerick, Ireland and Sport Ireland Institute, IIS Building, National Sports Campus, Abbotstown, Dublin 15, Ireland.

The purpose of this study was to compare peak force produced during the isometric mid-thigh pull (IMTP) and isometric squat (IsoSquat), performed at the same knee and hip angles (135 – 140°) and determine the reliability of both tests. Following a specific warm-up, 22 international athletes from different sports performed 2 maximal effort tests of both the IMTP and IsoSquat. Peak force achieved during the IsoSquat was significantly greater ($p = 0.01$) than peak force achieved during the IMTP. Both tests were highly reliable for peak force (ICC ≥ 0.97 ; CV $\leq 5\%$). Therefore, strength and conditioning coaches can select either test when examining lower extremity maximum strength. However, the IsoSquat produces higher peak force values and this may be a more accurate reflection of the athlete's maximum strength.

KEYWORDS: Isometric strength, maximum strength, performance testing

INTRODUCTION: Maximal force generating capabilities are commonly monitored in athletes. According to Juneja, Verma, and Khanna (2010) the isometric mid-thigh pull (IMTP) appears to be the most commonly used isometric assessment when attempting to evaluate the force-time curves of athletic populations. Nuzzo, McBride, Cormie, and McCauley (2008) reported that NCAA division I American footballers and track and field athletes produced 12% more peak force (PF) during an isometric squat (IsoSquat) compared with an IMTP performed at the same knee and hip angle (140°). This difference may be due to the elimination of the use of the upper extremity during the IsoSquat compared with the IMTP. This may be a potential advantage to athletes with weakness or dysfunction in their upper extremity. In particular, females may be at a greater disadvantage, as previous studies have established gender differences, especially of the upper body (Yanovich et al., 2008). This may leave females at a disadvantage in demonstrating lower extremity strength when performing an IMTP compared to an IsoSquat.

When reporting the reliability of PF, the majority of studies have only reported the intraclass correlation coefficient (ICC) as the reliability measure. To determine the reliability of a test, the intraclass correlation (ICC), coefficient of variation (CV) and 90% confidence intervals (90% CI) should be determined (Hopkins, 2000). Therefore, the level of reliability reported in some studies remains questionable. Additionally, the joint positions assumed for these tests differ across studies, with the knee angle for the IMTP ranging from 120 – 150° (Comfort, Jones, McMahon, & Newton, 2015; West et al., 2011) and the IsoSquat ranging from 90 – 150° (Blazevich, Gill, & Newton, 2002; Wilson, Lyttle, Ostrowski, & Murphy, 1995). This lack of consistency may adversely impact on the reliability of the measures. The purpose of this study was to compare peak forces achieved during the IMTP and IsoSquat performed at the same knee and hip angles and assess the reliability of both tests.

METHODS: Following ethical approval by the local University Research Ethics Committee, twenty two international athletes (Track and Field, Taekwondo, Canoeing, Rowing, Modern Pentathlon, Boxing and Badminton) were recruited for this study. This consisted of sixteen male participants, age: 22.8 ± 2.9 years; height: 179 ± 5.8 cm; body mass: 72.8 ± 10.4 kg and six female participants, age: 25.0 ± 2.0 years; height: 168.9 ± 3.3 cm; body mass: 62.9 ± 3.9 kg.

All isometric testing was conducted on a custom-made isometric Sortnex rack (Lexington, USA) anchored to the floor and placed over a Kistler force platform (Winterthur, Switzerland) sampling at 1000 Hz. The rack has small increments (0.5 cm) to allow for the desired position. Participants completed a familiarisation session. Firstly they were set in the correct position for the IMTP, i.e. a clean "2nd pull" position, which consisted of a mean knee angle of

THE RELATIONSHIP BETWEEN MAXIMUM STRENGTH AND ACCELERATION PERFORMANCE IN TRACK AND FIELD SPRINT ATHLETES

BRADY C.,¹ COMYNS T.,¹ HARRISON A.,¹ AND FLANAGAN E.²

¹University of Limerick, Ireland; and ²Sport Ireland Institute

Introduction: The determinants of the velocity-time curve of the 100 m are divided into 3 distinct phases, start-acceleration, maximum velocity and deceleration [1]. To achieve a higher maximal velocity, the acceleration from the blocks over the first 10 m followed by the subsequent acceleration has been shown to be directly related to performance [2]. It has been suggested, that performance in the 100 m is associated with athletes having a greater ability to apply a higher resultant ground reaction force during the acceleration phase [3]. Maximum isometric strength tests assess the neuromuscular ability of the lower limbs to produce maximal force during high-load, zero-velocity movements. The purpose of this study was to examine the relationship between peak force (PF) measured during an

isometric mid-thigh pull (IMTP) and isometric squat (ISqT) and acceleration performance in national level sprinters, thus providing the strength and conditioning practitioner with evidence concerning the use of strength training for sprinters.

Methods: Twenty five male ($n = 15$) and female ($n = 10$) sprinters (age 22.6 ± 3.3 years; height 175.1 ± 8.7 cm; mass 71.3 ± 8.2 kg and 100 m personal best 11.34 ± 0.48 seconds) were recruited. Each athlete was assessed for maximal strength, measured by peak force (PF) during the IMTP and ISqT and acceleration from blocks over 30 m, measured with timing gates at 5, 10, 20 and 30 m. Correlations were evaluated using Hopkins' scale [4]. **Results:** Results showed that significantly greater PF was produced during the ISqT compared to the IMTP ($p < 0.001$). There was a significant, strong relationship between PF measured during the IMTP ($1,810 \pm 584$ N) and sprint performance to 5 m (1.22 ± 0.08 seconds; $r = -0.675$, $p < 0.001$), 10 m (1.94 ± 0.08 seconds; $r = -0.671$, $p < 0.001$), 20 m (3.14 ± 0.13 seconds; $r = -0.673$, $p < 0.001$) and 30 m (4.26 ± 0.18 seconds; $r = -0.672$, $p < 0.001$). For the ISqT, a significant, strong relationship was found between PF ($2,142 \pm 628$ N) and 5 m time ($r = -0.643$, $p = 0.001$) and moderate significant relationships with 10 m ($r = -0.526$, $p = 0.007$), 20 m ($r = -0.488$, $p = 0.013$) and 30 m ($r = 0.417$, $p = 0.018$) times.

Discussion: Results from this study suggest that there may be a strong relationship between IMTP PF and overall acceleration performance. Results showed that maximum strength demonstrated during the ISqT having a stronger relationship with the early phase acceleration (0–5 m) compared with subsequent phases, suggesting that maximum strength is most related to the initial first steps from the blocks, where high ground reaction forces are being produced. This information could assist coaches in choosing appropriate tests for use in monitoring, identifying strength and weaknesses and helping with programme design. However, further research is needed to ascertain whether increasing maximal strength results in improved acceleration performance. **References:** [1] Ae, M, Ito, A, and Suzuki, M. The Scientific Research Project at the II World Championships in Athletics: Preliminary reports. The men's 100 metres. *New Studies Athletics* 7: 45–52, 1992. [2] Mero, A, Komi, P, and Gregor, R. Biomechanics of sprint running. *Sports Med* 13: 375–392, 1992. [3] Morin, B, Bourdin, M, Edouard, P, et al. Mechanical determinants of 100 m sprint running performance. *Eur J Appl Physiol* 112: 3921–3930, 2012. [4] Hopkins, W, Marshall, S, Batterham, A, et al. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc* 41: 3–13, 2009. This work is supported by the Irish Research Council and Sport Ireland Institute. **Mail to:** claire.bradyl@ul.ie.

The relationship between the isometric mid-thigh pull and acceleration performance in sprinters

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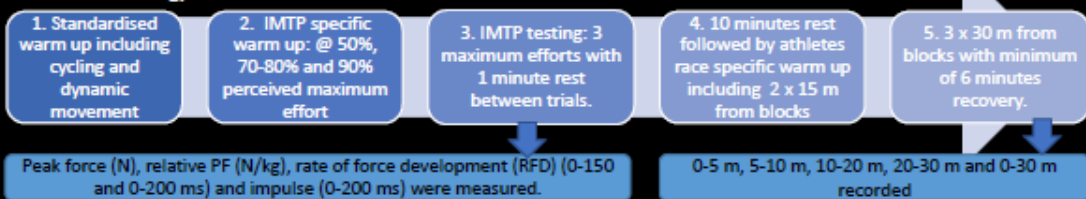
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INTRODUCTION

Coaches use a variety of training methods to develop appropriate strength qualities in athletes. Having an understanding of how these strength qualities differ to and having the capacity to select diagnostic tests that relate most specifically to sprinting is important. Therefore, the aim was to assess the relationship between the isometric mid-thigh pull (IMTP) and acceleration performance in sprinters and to investigate the differences in sprint times between relatively stronger and weaker athletes.

METHODS

PARTICIPANTS: Twenty five male (n = 15) and female (n = 10) sprinters (age 22.6 ± 3.3 years; height 175.1 ± 8.7 cm; mass 71.3 ± 8.2 kg) were recruited.



STATISTICS:

Data was normally distributed assessed using the Shapiro Wilk statistic ($p > .05$). Relationships were determined using Pearson product-moment correlations evaluated using Hopkins scale. ¹ Relatively stronger athletes were compared to weaker athlete by a median split using relative PF. *t* tests were reported with Holm's sequential Bonferroni and effect sizes (Hedges *g*) were calculated to determine the magnitude of differences between groups ²

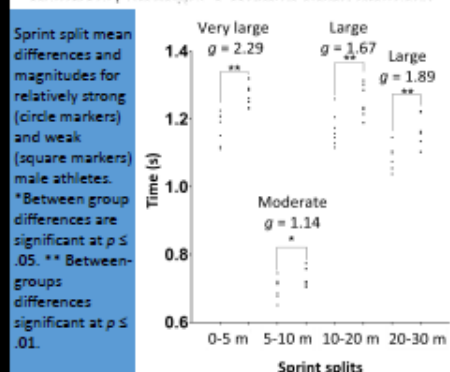
RESULTS

Variable	Males	<i>r</i> (0-5 m)	Females	<i>r</i> (0-5 m)
Peak Force (N)	2070 ± 548	-.626*	1420 ± 400	-.065
Rel PF (N/kg)	27.3 ± 7.2	-.527*	21.9 ± 5.4	-.201
RFD (0-150 ms)	7527 ± 1594	-.550*	5337 ± 2136	.016
RFD (0-200 ms)	6392 ± 1459	-.556*	4401 ± 1497	-.134
IMP (0-200 ms)	220 ± 51	-.582*	149 ± 48	.172

PF = peak force; Rel PF = peak force relative to body mass; RFD = rate of force development; IMP = impulse. Statistically significant correlations are in bold. * $p \leq .05$.

Variable	Strong (n = 7)	Weak (n = 7)	<i>p</i>	<i>g</i>	ES
Rel PF (N/kg)	34.1 ± 2.8	18.7 ± 3.7	.006	4.56	Very large

Relatively stronger v weaker male athletes



CONCLUSION:

Measures of isometric strength significantly correlate with 0 – 5 m sprint performance in male athletes. The test is able to distinguish between faster and slower male sprint athletes, with the faster athletes being relatively stronger than the slower athletes.

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