RESISTANCE TRAINING FOR SPRINTERS: THE ROLE OF MAXIMUM STRENGTH, REACTIVE STRENGTH AND EXERCISE SELECTION

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Abstract

Title: Resistance Training for Sprinters: The Role of Maximum Strength, Reactive Strength and Exercise Selection

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Each distinct phase of a 100 m sprint is dependent on key race variables e.g. acceleration ability, maximum velocity and speed endurance. Consequently, sprinters frequently supplement their sprint training with resistance training to develop qualities such as maximum strength and reactive strength. The literature assessing the association between these strength qualities and sprint performance has found contrasting results. Additionally, the literature on the prescription of resistance exercises to sprinters is sparse and consequently, evidence based prescription of resistance training is limited. Thus, the aims of this programme of research were to explore the relationship between race variables and 100 m time, explore the role of maximum strength and reactive strength in sprinting and to investigate the prescription and suitability of resistance training exercises for sprinters. Chapter 3 investigated world class male 100 m sprint performance data and found that the acceleration-time constant was an excellent indicator of relative acceleration ability and therefore merits monitoring. Furthermore, maximum velocity was highly related to each 20 m section of the sprint (r = -0.57 to -0.98) and overall 100 m time (r = -0.97) highlighting the crucial importance of maximum velocity to a 100 m sprinter. Chapter 4 investigated the relationship between maximum strength, reactive strength and maximum velocity, 10 m split times and sprint mechanical properties assessed during a 40 m sprint. Peak force and relative force, measured in an isometric mid-thigh pull, and reactive strength index, measured in drop jumps and hopping, had no statistically significant relationship with any of sprint performance measures. However, a high correlation (r = 0.61) was found between peak force and peak horizontal power in men only. The lack of a significant relationship between drop jump reactive strength and any of the sprint performance measures indicated that the use of the reactive strength index as a measure of an athlete’s reactive strength warranted further investigation. Consequently, Chapter 5 assessed how differing performance strategies affect measures of reactive strength in drop jumps. Limiting group variance in contact time was recommended to improve the validity of reactive strength measurements. In Chapter 6 a survey of sprint coaches’ prescription of resistance training exercises was conducted with the hurdle jump found to be the most widely prescribed exercise (93% of coaches). Based on the findings of Chapter 6, a biomechanical comparison between the kinematics of maximum velocity sprinting and hurdle jumping was conducted in Chapter 7. Based on Chapter 7’s findings, the hurdle jump is recommended as a suitable exercise for sprinters due to the greater demand placed on the athlete to reverse the velocity of their centre of mass, similar peak knee extension angular velocities and greater ankle dorsiflexion angular velocities. Common themes emerging from the thesis are also discussed including the implications for using ratio-based measures, using ground contact time as a monitoring tool and recommendations for individualised assessment and training.
Authors Declaration

I hereby declare that the work contained in this thesis is my own, and was completed under the supervision of Prof. Andrew Harrison and Dr. Ian Kenny of the Department of Physical Education and Sport Sciences, University of Limerick. This work has not been submitted to any other university or higher education institution, or for any other academic award within this University.

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List of Abbreviations

\( \Theta_{\text{MaxAnk}} \): Maximum ankle angle
\( \Theta_{\text{MaxHip}} \): Maximum hip angle
\( \Theta_{\text{MaxKnee}} \): Maximum knee angle
\( \Theta_{\text{MinAnk}} \): Minimum ankle angle
\( \Theta_{\text{MinHip}} \): Minimum hip angle
\( \Theta_{\text{MinKnee}} \): Minimum knee angle
\( \omega_{\text{Ank}} \): Ankle angular velocity
\( \omega_{\text{Hip}} \): Hip angular velocity
\( \omega_{\text{Knee}} \): Knee angular velocity
\( \omega_{\text{MeanAnk}} \): Average ankle angular velocity
\( \omega_{\text{MeanHip}} \): Average hip angular velocity
\( \omega_{\text{MeanKnee}} \): Average knee angular velocity
\( \omega_{\text{PeakAnk}} \): Peak ankle angular velocity
\( \omega_{\text{PeakHip}} \): Peak hip angular velocity
\( \omega_{\text{PeakKnee}} \): Peak knee angular velocity
\( \tau \): Acceleration time constant
\( \tau_{\text{AnkCon}} \): Concentric phase average ankle joint torque
\( \tau_{\text{AnkEcc}} \): Eccentric phase average ankle joint torque
\( \tau_{\text{HipCon}} \): Concentric phase average hip joint torque
\( \tau_{\text{HipEcc}} \): Eccentric phase average hip joint torque
\( \tau_{\text{KneeCon}} \): Concentric phase average knee joint torque
\( \tau_{\text{KneeEcc}} \): Eccentric phase average knee joint torque
1 RM: One repetition maximum
\( B\text{F}_{\text{EMG}} \): Biceps femoris average EMG
BT: Braking time
CI: Confidence interval
COM: Centre of mass
CSCS: Certified Strength and Conditioning Specialist
CT: Contact time
CV: Coefficient of variation
ES: Effect size

$F_{0}$: Theoretical maximum horizontal component of ground reaction force

$F_{aero}$: Aerodynamic drag force

$F_{\text{Dr}-}$: Resultant force direction in braking phase

$F_{\text{Dr}+}$: Resultant force direction in propulsion phase

$FH^{-}$: Average horizontal braking force

$FH^{+}$: Average horizontal propulsion force

FPT: Force production time

$FR^{-}$: Average resultant force in braking phase

$FR^{+}$: Average resultant force in propulsion phase

$FV^{-}$: Average vertical braking force

$FV^{+}$: Average vertical propulsion force

FT: Flight time

$GAS_{\text{EMG}}$: Gastrocnemius average EMG

$GM_{\text{EMG}}$: Gluteus maximus average EMG

GRF: Ground reaction force

IAAF: International Association of Athletics Federations

ICC: Intraclass correlation coefficients

$I_{H^{-}}$: Horizontal braking impulse

$I_{H^{+}}$: Horizontal propulsion impulse

$I_{V^{-}}$: Vertical braking impulse
IVP: Vertical propulsion impulse
IMTP: Isometric mid-thigh pull
JH: Jump height
Kvert: Vertical stiffness
LOA: Limits of agreement
NFL: National Football League
MVC: Maximum voluntary contraction
NSCA: National Strength and Conditioning Association
PAnkNeg: Average negative ankle joint power
PAnkPos: Average positive ankle joint power
Pmax: Maximum horizontal mechanical power
PB: Personal Best
PF: Peak force
PH: Horizontal braking power output
PH+: Horizontal propulsive power output
PHipPos: Average positive hip joint power
PKneeNeg: Average negative knee joint power
PKneePos: Average positive knee joint power
PT: Propulsion time
RFEMG: Rectus femoris average EMG
RI: Resultant impulse
RPF: Resultant peak force
RSI: Reactive strength index
RSR: Reactive strength ratio
RT: Reaction time
RT: Resistance Training
SF: Stride / step frequency
SL: Stride / step length
SSC: Stretch shortening cycle
\( T_{\text{Landing}} \): Landing time
\( T_{\text{Push}} \): Push off time
\( v \): velocity
\( v_0 \): Theoretical maximum horizontal velocity
\( v_{\text{hmax}} \): Maximal horizontal velocity
\( v_{\text{Loss}} \): velocity lost relative to maximum velocity.
\( V_{\text{LEMG}} \): Vastus lateralis average EMG
\( v_{\text{TO}} \): Resultant take-off velocity
Submissions and Publications Arising from and Related to the Thesis

Chapter 3: Healy, R, Kenny, I.C, and Harrison, A.J. (UNDER REVIEW) Profiling Elite Male 100 m Sprint Performance: The Role of Maximum Velocity and Relative Acceleration. *Journal of Sport and Health Science*


Chapter 1: Thesis Introduction
1.1 Introduction
The 100 m sprint is one of the most prestigious events in sport and it has been an Olympic event for men and women since 1896 and 1928 respectively. The goal of the 100 m sprint is simple; the athlete must complete a distance of 100 m as quickly as possible while staying in their lane. The athlete that achieves this in the quickest time wins. In 1912, the very first International Association of Athletics Federations (IAAF) recognised men’s 100 m record was set by Donald Lippincott of the United States of America with a time of 10.60 s (IAAF 2009). Ten years later, in 1922, the IAAF recognised the first women’s 100 m record; set by Marie Mejzlíková II of Czechoslovakia with a time of 13.60 s (IAAF 2009). Over a hundred years later substantial developments in timing technology, track surfaces, coaching and training methods and increased participation in track and field athletics, the 100 m men’s record and 100 m women’s record have fallen to 9.58 s, set by Usain Bolt of Jamaica in 2009, and 10.49 s by Florence Griffith-Joyner of the United States of America in 1988 respectively. A sprint time can only be considered eligible for a record if several criteria are met; an electronic timing system must be used, the sprinter’s reaction time in the blocks must be ≥ 0.100 s, the sprint must be completed with a legal wind i.e. any wind speed less than a tailwind of ≤ 2.00 m·s\(^{-1}\) and the sprinter must not have used any prohibited substance.

The mechanical analysis of sprinting requires an understanding of mechanics i.e. Newton’s laws of motion. According to Newton’s First law, a body at rest remains at rest and a body in uniform motion remains in uniform motion unless acted on by an unbalanced force. A sprinter in the set position of the blocks is in a state of rest and thus a force must be applied if they are to initiate a change of motion. Newton’s Second law states that the rate of change of momentum i.e. acceleration, of a body is directly proportional to the force applied and this acceleration occurs in the direction of the applied force. As a sprinter has a constant mass, greater applied forces will result in greater accelerations of the sprinter’s centre of mass (COM). According to Newton’s Third law, when one body exerts a force on a second body that second body will exert a force equal in magnitude and opposite in direction on the first body. During a sprint, the sprinter applies a force (action force) against the blocks or the ground and consequently, the blocks or the ground exert an equal but opposite force (the ground reaction force) back on the sprinter and thus the sprinter’s COM accelerates forwards.
Force is a vector, and therefore has a magnitude and a direction. In relation to sprinting, the resultant ground reaction force can be broken down into three orthogonal components but only the vertical component and the anterior-posterior or horizontal component merit attention (Hunter et al. 2005). The vertical component of force acts to overcome the downward acceleration that occurs due to gravity and following this develops a vertical impulse to propel the COM upwards and into the air so that the sprinter has sufficient time to reposition their limbs for the subsequent step (Weyand et al. 2000; Hunter et al. 2005). The horizontal component of force acts to develop an impulse that will either cause a net braking effect or a net propulsive effect i.e. a decrease or increase the horizontal velocity of the sprinter’s COM respectively (Hunter et al. 2005; Morin et al. 2015). Consequently, any training or coaching method directed at improving sprint performance, during the stance phase of a sprint, is designed to cause a net positive change either through the application of greater forces or the optimisation of how the forces are directed (Weyand et al. 2000; Weyand et al. 2010; Morin et al. 2015).

Sprinting necessitates the production of large forces over short time intervals and consequently, sprint coaches utilise various training methods with their athletes to develop different force production qualities (Delecluse 1997; Bolger et al. 2016; Whelan et al. 2016; Bezodis et al. 2018). Sprinting can be viewed as a multidimensional skill with different phases e.g. acceleration, maximum velocity and deceleration, and different kinematic and kinetic requirements existing during each distinct phase (Delecluse et al. 1995). Furthermore, key factors such as a sprinter’s ability to accelerate rapidly, achieve a high maximum velocity and maintain that velocity are crucial to success. How these factors relate to one another has yet to be investigated in an elite sprinter population.

Although sprint training is the most important training modality for sprinters, resistance training is frequently performed to supplement the work carried out on the sprint track and develop qualities such as strength and power which are inherently linked to speed (Delecluse 1997; Bolger et al. 2016; Bezodis et al. 2018; Nagahara and Zushi 2017). Strength exists in various forms and each specific type of strength is generally characterised based on the specific conditions e.g. movement velocity, under which the force is produced. Maximum strength exists on one end of the force-velocity curve and has been defined as the ability to voluntarily generate maximum force at very low velocities (Sale and Norman 1991). Several authors have found a significant relationship between maximum strength and sprint
performance measures such as maximum velocity and 100 m sprint time, in sprint athletes (Young et al. 1995; Meckel et al. 1995; Bret et al. 2002). These studies have focused only on simple measures such as sprint time and sprint velocity. Consequently, the association between maximum strength and sprint mechanical properties merits investigation to further the current understanding about the role of maximum strength and sprint speed.

Reactive strength exists on the opposite end of the force-velocity curve and has been defined as the ability to rapidly develop force at high movement velocities and under a high eccentric load (Lockie et al. 2015). An additional distinction between maximum strength and reactive strength is that reactive strength is expressed in movements utilising the stretch shortening cycle (SSC) i.e. where a lengthening (eccentric) contraction is quickly followed by a shortening (concentric) contraction, whereas maximum strength is not (Komi 2000). This distinction is important as the stretch shortening cycle is utilised in every step of a sprint apart from the initial push off the blocks. Research assessing the association between reactive strength and sprint performance in sprinters has found conflicting results (Young et al. 1995; Hennessy and Kilty 2001, Smirniotou et al. 2008; Nagahara et al. 2014). This is potentially due to the method used to assess reactive strength as several modalities e.g. drop jump, rebound jump and hopping, have been used with differing instructions. Consequently, the relationship between reactive strength and sprint performance requires clarification.

Different strength qualities will play relatively greater roles throughout the different phases of a sprint (Nagahara et al. 2014). Accordingly, coaches typically prioritise different strength qualities at different times of a season with greater emphasis placed on maximum strength in the beginning of a season and greater emphasis placed on reactive strength as the competition phase approaches (Bolger et al. 2016; Bezodis et al. 2018). The exercises coaches utilise to achieve these training goals can vary greatly and there is a paucity of research, in a sprinter population, to support the inclusion and exclusion of specific resistance training exercises for the distinct phases of sprinting (Bolger et al. 2015; Bolger et al. 2016). Only one study has been conducted assessing elite sprint coaches’ prescription of resistance training exercises to their athletes and this used only a small sample size (Bolger et al. 2016). Consequently, further research is necessary to identify the resistance training exercises prescribed by a larger range of sprint coaches. Furthermore, opposition exists to the inclusion of specific resistance training exercises by some expert coaches due to a perceived lack of biomechanical suitability (Bolger et al. 2016). Evidence to support the selection of resistance
training exercises is encouraged and thus research assessing the suitability of selected resistance training exercises by comparing their kinematics to sprinting is warranted.

1.2 Thesis Aims
The aims of this programme of research were to explore the importance of 100 m sprint race variables to overall 100 m time, advance the understanding of the role of maximum strength and reactive strength in sprint performance and to investigate the prescription of resistance training exercises and their suitability for sprint athletes.

1.3 Thesis Objectives
- Identify the role of maximum velocity and relative acceleration in 100 m performance and to investigate the differences in sprint performance between “faster” and “slower” elite male sprinters.
- Investigate the relationship between maximum strength, reactive strength and sprint performance in male and female sprinters.
- Identify why sprint coaches prescribe resistance training to their athletes and determine what the most widely prescribed exercises are and why they are prescribed.
- Assess the ground contact phase kinematic differences between maximum velocity sprinting and the most widely prescribed resistance training exercise in male sprinters.

1.4 Thesis Overview
This thesis is divided into nine progressively linked chapters. Experimental chapters (3-8) have been prepared in a journal paper ready format with all chapters ready for submission (Chapter 7), currently under peer review (Chapter 3), accepted for publication (Chapter 6) and published (Chapters 4-5). The following paragraphs give a brief summary of each chapter and outline the contribution of each chapter to the overall aims of the thesis.

1.4.1 – Chapter 2: Literature Review
Chapter 2 provides a comprehensive review of existing literature on the sprint phases, the biomechanics of maximum velocity sprinting, the effects of resistance training on sprinters, the specificity of resistance training exercises for sprinting and the role of maximum strength and reactive strength in sprint performance.
1.4.2 – Chapter 3: Profiling Elite Male 100 m Sprint Performance: The Role of Maximum Velocity and Relative Acceleration.

Chapter 3 assessed the accuracy of a four split modelling method to derive velocity-distance and velocity-time data of elite male 100 m sprinters during major international sprint competitions. This chapter subsequently assesses the differences between “faster” and “slower” sprinters and assesses the role of key race variables: maximum velocity, relative acceleration and deceleration ability on 100 m performance.

1.4.3 – Chapter 4: Influence of Reactive and Maximum Strength Indicators on Sprint Performance

Chapter 4 investigates the relationship between reactive strength, measured in a drop jump and a vertical hop test, maximum strength, measured using an isometric mid-thigh pull, and sprint times, maximum velocity, and mechanical properties measured over 40 m.

1.4.4 – Chapter 5: Reactive Strength Index: A Poor Indicator of Reactive Strength?

Chapter 5 investigates the relationship between reactive strength measures, the reactive strength index and reactive strength ratio, and kinematic and kinetic measures during drop jumping in male and female sprinters. Additionally, this chapter highlights several issues with the use of the aforementioned reactive strength measures and provides practical recommendations for coaches and researchers alike.

1.4.5 – Chapter 6: Resistance Training Practices of Sprint Coaches

Chapter 6 describes the results of a survey of resistance training practices of sprint coaches (n = 41). The study investigates why sprint coaches prescribe resistance training to their athletes, what exercises they select and what factors are involved with their selection. This study provides a list of resistance training exercises commonly prescribed by sprint coaches and directs the kinematic analysis performed in Chapter 7.

1.4.6 – Chapter 7: Kinematic Differences Between Maximum Velocity Sprinting and Hurdle Jumping in Male Sprint Athletes

Chapter 7 assesses the differences in the ground contact phase kinematics: ground contact times, ankle, knee and hip angles and angular velocities and the vertical velocities of the centre of mass and lower leg between maximum velocity sprinting and hurdle jumps performed over 0.60, 0.75 and 0.90 m hurdles.
1.4.7 – Chapter 8: Thesis Conclusions and Implications

Chapter 8 provides a discussion on the key findings and applications of the current body of work. Chapter 8 also discusses the limitations to the current research and provides recommendations for future research in the area.
Chapter 2: Literature Review
2.1 100 m Sprint Phases

The 100 m sprint can be viewed as a multidimensional skill as it can be divided into several technical phases with specific kinematic and kinetic characteristics present in each phase (Delecluse et al. 1995). There is no consensus in the sprint literature about the exact number of phases and where exactly they occur (Jones et al. 2009; Mackala 2007). However, sprint coaches do agree that a 100 m sprint race has a beginning, middle and an end (Jones et al. 2009). Furthermore, expert sprint coaches identified three phases of the 100 m sprint: the start phase, the drive/pick up phase and the maintenance phase (Jones et al. 2009). The start phase was defined as the set position in the starting blocks to the point where the front foot left the block. The drive/pick up phase takes place between the front foot leaving the block to the point the athlete adopts an upright sprinting position. The maintenance phase was defined as the remainder of the race i.e. the time between the adoption of the upright sprinting posture and the end of the race (Jones et al. 2009).

In the scientific literature on race phases, the 100 m sprint has traditionally been divided into the acceleration phase, the maximum velocity phase and the deceleration phase (Mackala 2007; Ryu et al. 2012; Maćkała et al. 2015; Slawinski et al. 2017). These phases have typically been identified by assessing the changes that occur in a sprinter’s velocity or sprint step kinematics i.e. step length and step frequency, throughout the 100 m sprint. Each phase can be further subdivided however, these sub divisions vary considerably within the literature.

2.1.1 The Acceleration Phase

The acceleration phase consists of the sprint start from the blocks and ends when maximum velocity is achieved. Jones et al. (2009) reported in interviews that, four out of seven expert sprint coaches believed that a race could be won in the first two strides and consequently the sprint start was considered to be technically crucial to the outcome of the 100 m sprint. The sprint start time can be divided into the reaction time and the block clearance time (Graham and Harrison 2006). The reaction time is defined as the time elapsed from the gun’s signal to the instant force is produced whereas the block clearance time is the time taken for the front foot to leave contact (Mero and Komi 1990; Graham and Harrison 2006; Debaere et al. 2013a).
Tønnessen et al. (2013) assessed the relationship between reaction time and 100 m sprint time during world championships between 2003 and 2009 and found that shorter reaction times were significantly correlated with faster 100 m times in male (r = 0.292) and female (r = 0.328) sprinters. These findings highlight the importance of short reaction times to a 100 m sprinter.

There is conflicting research regarding the difference in block clearance time between faster sprinters and their slower counterparts. Slawinski et al. (2010) found no difference in mean block clearance time between elite (mean ± SD 100 m PB of 10.27 ± 0.14 s; block clearance time: 0.352 ± 0.018 s) and well-trained (mean ± SD 100 m PB = 11.31 ± 0.28 s; block clearance time: 0.351 ± 0.020 s) sprinters. Contrary to this, Willwacher et al. (2013) compared world-class male sprinters (mean ± SD 100 m PB of 10.06 ± 0.28 s) and fast but relatively slower male sprinters (mean ± SD 100 m PB = 11.08 ± 0.21 s). The world-class male sprinters achieved shorter block clearance times compared to fast sprinters (mean ± SD: 0.34 ± 0.02 s versus 0.39 ± 0.03 s, p < 0.001). Willwacher et al. (2013) reported that the shorter clearance times found in world class sprinters were due to the application of higher forces with higher rates of force development during the sprint start. In contrast, Ciacci et al. (2017) found that faster sprinters, regardless of sex, had longer block clearance time, tended to assume a lower vertical position of the COM in the set position, achieved through greater knee flexion of the front leg, and a lower vertical velocity of the COM on block clearance. Bezodis et al. (2010) identified the normalised average horizontal power as the most appropriate method of quantifying sprint start performance as it incorporates how well a sprinter increases their velocity and the length of time taken to achieve this while also accounting for body mass.

The duration of the acceleration phase will depend on the level of the sprinter as faster sprinters typically achieve higher maximum velocities and thus accelerate over a longer distance (Volkov and Lapin 1979; Mackala 2007; Maćkala et al. 2015; Slawinski et al. 2017). Additionally, the acceleration phase has sometimes been divided into two further phases: the initial acceleration phase, approximately taking place over the first 10-20 m, and the secondary / extended acceleration or pick up phase which approximately takes place over the next 20 m (Delecluse et al. 1995; Delecluse 1997; Mackala 2007; Maćkala et al. 2015; Manzer 2016). During the initial acceleration phase, there is a rapid increase in sprinting velocity due to increases in stride length and stride frequency (Delecluse et al. 1995; Mackala
During the subsequent acceleration phase, there is a further increase in sprint velocity, largely due to increases in stride length, however these changes are less pronounced than the initial acceleration phase (Mackala 2007; Krzysztof and Mero 2013).

### 2.1.2 The Maximum Velocity Phase

In the maximum velocity phase, there is a gradual increase in the sprinter’s velocity, which is represented as a relatively flat section on a velocity-distance curve with the sprinter’s velocity typically around 95-100% of maximum velocity (Seagrave et al. 2009). Maximum velocity is attained when a sprinter can no longer accelerate and thus, the maximum velocity phase of sprinting is dependent on the level of the sprinter (Volkov and Lapin 1979; Maćkała 2007). Accordingly, the location of the maximum velocity phase in a 100 m sprint varies within the literature. Mackala (2007) compared the sprint phases of male national level sprinters (Mean 100 m time = 11.18 s) and the eight male 100 m sprint finalists in the 1991 IAAF World Championships. In the national level sprinters, the 40-60 m section was considered the maximum velocity phase whereas the 60-70 m phase was identified as the maximum velocity phase in the elite sprinters. A comprehensive review of the biomechanics of maximum velocity sprinting is given below in section 2.2.

### 2.1.3 The Deceleration Phase

Although the optimal race strategy in the 100 m sprint is to employ maximum effort i.e. no pacing, there is an inevitable decrease in velocity due to fatigue and this leads to a transition from the maximum velocity phase to the deceleration phase (van Ingen Schenau et al. 1994; Slawinski et al. 2017). The decrease in velocity continues until the athlete crosses the finish line. The beginning of the deceleration phase will vary between individual sprinters as higher-level athletes typically accelerate for longer and thus begin decelerating later (Volkov and Lapin 1979; Mackala 2007; Maćkała et al. 2015; Slawinski et al. 2017). Consequently, the literature has defined the deceleration phase using different starting points with some studies using the 60-100 m section of a 100 m sprint (Delecluse et al. 1995; Bret et al. 2002; Smirniotou et al. 2008) and others using the 80-100 m section (Mackala 2007; Ryu et al. 2012).

### 2.2 Maximum Velocity Biomechanics

A plethora of research has investigated the biomechanics of maximum velocity sprinting. This research has typically focused on descriptive studies assessing high level sprinters,
assessing differences between the acceleration and maximum velocity phases of sprinting, assessing differences between maximum velocity sprinting and sub-maximum velocity sprinting, assessing sex differences in maximum velocity sprint biomechanics and investigating differences between sprint specialists and non-sprint specialists and between relatively faster and slower sprinters.

2.2.1 Step / Stride Characteristics

The sprint step consists of half of a running cycle i.e. the time elapsed between the initial contact of one foot with the ground and the initial contact of the opposite foot with the ground (Hunter et al. 2004). The sprint stride consists of a full running cycle i.e. the time elapsed between the initial contact of one foot with the ground and the next contact of the same foot with the ground (Hunter et al. 2004). Horizontal sprint velocity is the product of step / stride rate and step / stride length. The deterministic model by Hay (1994) provides the determinants of step rate and length and is given in Figure 2.1 and 2.2. An improvement in one factor will result in an increase in sprint velocity if the other factor remains constant (Salo et al. 2011).

Figure 2.1: The deterministic model for step rate (Hunter et al. 2004). GRI = Ground reaction impulse.
Figure 2.2: The deterministic model for step length (Hunter et al. 2004). GRI = Ground reaction impulse.

It is, however, also possible for an increase in one factor to result in a decrease in the other factor; this is known as a negative interaction (Hunter et al. 2004). Hunter et al. (2004) found that leg length, height of take-off and vertical velocity of take-off were the most prominent sources of a negative interaction between step length and step frequency. Debaere et al. (2013b) found a very strong to near perfect negative correlation between step length and step frequency in male sprinters ($r = -0.91$) and female sprinters ($r = -0.77$) sprinting at maximum velocity. Additionally, Hunter et al. (2004) suggested that the very high step lengths and step rates achieved by elite athletes may only be possible by high horizontal and low vertical take-off velocities.

Salo et al. (2011) investigated whether elite male athletes are individually more reliant on step frequency or step length. The authors assessed the average step rate and step length for 11 athletes in ≥10 100 m races in major competitions. Individual differences were found in step frequency and step length reliance as three athletes were determined to be step length reliant whereas only one athlete was step frequency reliant. The remaining six athletes had no consistent reliance. These results suggest that no clear reliance on step length or step frequency exists for elite sprinters, from a group perspective, and each sprinter’s individual reliance should be reflected in their training programme.
Debaere et al. (2013a) assessed the differences in step characteristics between high-level male and female sprinters during a 60 m sprint. The men achieved significantly higher maximum velocities (10.01 ± 0.16 m·s⁻¹ versus 8.88 ± 0.11 m·s⁻¹), higher step frequencies (4.43 ± 0.18 Hz versus 4.28 ± 0.17 Hz) and longer step lengths (2.22 ± 0.10 m versus 1.99 ± 0.13 m) during the maximum velocity phase compared to the women. The difference in step frequencies were largely due to significantly shorter contact times (0.106 ± 0.006 s versus 0.112 ± 0.006 s) as no significant difference was found in the flight times (0.121 ± 0.010 s versus 0.123 ± 0.007 s). Manzer et al. (2016) also assessed gender differences in maximum velocity sprinting. The men achieved significantly higher maximum velocities (9.20 ± 0.30 m·s⁻¹ versus 8.00 ± 0.30 m·s⁻¹) and longer stride lengths (4.33 ± 0.22 m versus 3.91 ± 0.19 m) with no significant difference found in stride frequency (2.18 ± 0.48 Hz versus 2.10 ± 0.11 Hz) compared to the women.

Yu et al. (2016) assessed the biomechanical differences between the acceleration phase and maximum velocity phases in male sprinters (100 m personal best (PB): 10.94 ± 0.32 s). Statistically significantly higher stride frequencies (2.06 ± 0.15 Hz versus 1.99 ± 0.19 Hz) and longer stride lengths (4.50 ± 0.32 m versus 3.98 ± 0.27 m) were found in the maximum velocity phase compared to the acceleration phase. The difference in stride frequency was largely due to significantly shorter contact time (0.128 ± 0.009 s versus 0.145 ± 0.014 s) as no significant difference was found in swing times (0.359 ± 0.035 s versus 0.363 ± 0.046 s).

Bushnell and Hunter (2007) assessed the differences in maximum velocity sprint biomechanics between specialist distance runners and specialist sprinters. The sprinters achieved significantly faster maximum velocities (9.35 m·s⁻¹ versus 8.40 m·s⁻¹) shorter contact times (0.109 s versus 0.124 s) and longer stride lengths (4.45 m versus 4.04 m).

In summary, sprint velocity is the product of step frequency and step length. A negative interaction occurs if one factor increases and causes a decrease in the other factor. There is no clear reliance on step frequency or step length in elite athletes with considerable individual differences existing. Significantly higher velocities are found in the maximum velocity phase relative to accelerative sprinting due to longer step lengths and higher step frequencies. Elite male sprinters can achieve higher sprinting velocities predominantly through longer step lengths compared to elite female sprinters. Additionally, sprint specialists can achieve higher step frequencies, through shorter contact times, and longer step lengths than non-sprinters.
2.2.2 Ground Reaction forces

Force can only be applied to the ground during the stance phase of a step. The ground reaction force (GRF) can be broken into three orthogonal components although the vertical and horizontal forces are of greatest concern to researchers (Hunter et al. 2005). The horizontal component of force can be further divided into the braking force which occurs when the GRF is directed posteriorly and the propulsive force which occurs when the GRF is directed anteriorly (Hunter et al. 2005). Several authors have investigated the role of horizontal and vertical forces in the acceleration phase and maximum velocity phase. Hunter et al. (2005) assessed the relationships between horizontal and vertical ground impulses and sprint kinematics during acceleration. Hunter et al. (2005) found that faster sprinting velocities, during acceleration, were largely accounted for by higher relative horizontal impulse ($R^2 = 0.61$) whereas the relative vertical impulse only accounted for 17% of the variance. Furthermore, the horizontal impulse was divided into the propulsive and braking phase with the relative propulsive impulse accounting for 57% of variance in sprinting velocity and no significant relationship found for the braking impulse.

Consistent with the previous findings, Yu et al. (2016) found that the application of larger propulsive forces and lower braking forces were key factors in achieving greater acceleration in male sprinters. Additionally, a lower braking duration and a higher propulsive duration, as a percentage of the total stance phase, was found in accelerative sprinting compared to maximum velocity sprinting. At maximum velocity no further horizontal acceleration is possible as there is no net horizontal force due to the athlete’s braking force, propulsive force and the force required to overcome air resistance summing to zero. Slawinski et al. (2017) found that, in world-class male and female sprinters, the ability to continue to produce horizontal forces at very high sprinting velocities was very highly correlated to 100 m sprint time. These findings are supported by Coyler et al. (2018) who performed a waveform analysis of ground reaction forces of male sprinters and soccer players sprinting at high velocities (8 – 8.5 m·s$^{-1}$). The sprinters were capable of producing higher horizontal force, across the majority of the propulsive phase, and were better able to attenuate force in the late braking phase compared to the soccer players.

Using a sprint treadmill design, Weyand et al. (2000) showed that faster maximum sprinting velocities were achieved by subjects by applying greater stance averaged vertical forces to the ground and not by repositioning their limbs more rapidly. Additionally, the limit to an
athlete’s maximum velocity is reached when the ground contact times and effective vertical impulses reach minimum values that still enable sufficient aerial time to reposition their swing leg for the subsequent step. Weyand et al. (2010) assessed whether stance phase limitations in vertical force application were imposed by ground reaction force maximums or by the extremely short ground contact times by comparing maximum velocity sprinting to backward running and one-legged hopping. Weyand et al. (2010) found that vertical forces applied to the treadmill in one legged hopping were greater than those during sprinting but the ground contact times were significantly longer. Consequently, the stance phase limit to maximum velocity is imposed by the minimum time needed to apply large mass specific vertical forces (vertical ground reaction force relative to body mass) and not by the maximum forces the limbs can apply.

Faster athletes produce larger stance averaged vertical forces than slower athletes but there are also differences in how the forces are applied. Clark and Weyand (2014) compared vertical force-time waveforms during maximum velocity sprinting between competitive sprinters and non-sprinters. The non-sprinters’ vertical force-time waveforms were consistent with the waveforms predicted by the spring mass model i.e. a symmetrical vertical force waveform similar to a half-sine waveform. In contrast, the competitive sprinters’ waveform deviated significantly from the non-sprinters’ waveforms with greater vertical forces observed during the first half of stance and no significant difference found in the second half of stance. Consistent with this, Nagahara and Zushi (2017) found that increases in maximum sprinting velocity over a six month period of training, coincided with increases in vertical force during the braking phase of stance only. The asymmetrical application of vertical forces is achieved by the impact-phase limb deceleration mechanism where the swing leg is forcefully driven into the ground at touchdown (Clark and Weyand 2014). Faster sprinters are capable of achieving greater knee elevation late in the swing phase and thus can achieve higher magnitude limb velocities prior to touchdown by punching their foot into the ground (Clark and Weyand 2014). This strategy enables higher peak vertical forces to be applied earlier during the stance phase compared to non-sprinters (Clark and Weyand 2014).

2.2.3 Joint Kinematics and Kinetics
The stance phase kinematics and kinetics of the ankle, knee and hip joint during maximum velocity sprinting have been frequently described within the literature.
2.2.3.1 Joint Angles

At the onset of the stance phase the ankle dorsiflexes progressively until peak dorsiflexion is achieved, typically around mid-stance, and then undergoes plantarflexion until take-off (Mann and Hagy 1980; Mero et al. 1987; Stefanyshyn and Nigg 1998; Bezodis et al. 2008; Nagahara and Zushi 2017). The knee angle initially flexes until mid-stance where it then begins to extend until just prior to take-off where extension ceases. (Mero et al. 1987; Kuitunen et al. 2002; Bezodis et al. 2008; Nagahara and Zushi 2017). In contrast, the hip angle undergoes extension throughout the entire stance phase (Mann and Hagy 1980; Mero et al. 1987; Kuitunen et al. 2002; Bezodis et al. 2008). The joint angles and angular velocities for the ankle, knee and hip during the stance phase of maximum velocity sprinting are illustrated in Figure 2.3.
Figure 2.3: The ankle, knee and hip joint angles and joint angular velocities adapted from Kuitenen et al. (2002) and Bezodis et al. (2008).
2.2.3.2 Joint Moments

Throughout the stance phase, the ankle moment is predominantly a plantar flexor moment (Mann and Sprague 1983; Stefanyshyn and Nigg 1998; Kuitenen et al. 2002; Bezodis et al. 2008; Schache et al. 2011; Nagahara and Zushi 2017) although some studies have reported a small dorsiflexor moment at the very beginning of stance (Nagahara and Zushi 2017) and just before take-off (Bezodis et al. 2008; Schache et al. 2011). The plantarflexor moment increases progressively throughout the braking phase until it reaches a peak value around mid-stance and then progressively decreases until take-off (Stefanyshyn and Nigg 1998; Kuitenen et al. 2002; Bezodis et al. 2008; Schache et al. 2011; Nagahara and Zushi 2017).

Mann (1983) found a knee flexor-extensor moment pattern with the knee extensor moment taking up the majority of the stance phase and with a brief flexor moment occurring at the beginning of stance which acts to extend the knee. Similarly, Kuitenen et al. (2002) and Nagahara and Zushi (2017) found a knee flexor-extensor-flexor moment pattern with the knee extensor moment taking up the majority of the stance phase and with a brief flexor moment occurring at the beginning of stance and again just before take-off which acts to terminate ground contact. In contrast, Bezodis et al. (2008) found a flexor-extensor-flexor-extensor-flexor pattern for the knee moment although similar to the work of Kuitenen et al. (2002) and Nagahara and Zushi (2017), the knee flexor moments occurred at the beginning of stance and just before take-off. Similar to the ankle moment, the peak knee extensor moment occurs around mid-stance although some individual variation has been reported (Bezodis et al. 2008).

The hip moment follows an extensor-flexor pattern with the hip moment predominantly extensor during the first half to two thirds of stance with the remainder of stance predominantly flexor (Mann 1983; Kuitenen et al. 2002; Bezodis et al. 2008). Both Mann, (1983) and Kuitenen et al. (2002) found a single peak pattern with the peak hip extensor moment occurring in the first third of stance. In contrast, Schache et al. (2011) and Bezodis et al. (2008) both found that the hip extensor moment throughout the first half of stance had a double peak with a larger peak after initial contact (20% of stance phase) with a smaller peak around mid-stance.

In summary, during maximum velocity sprinting the ankle moment is predominantly a plantar flexor moment, the knee follows a flexor-extensor-flexor moment pattern and the hip follows an extensor-flexor pattern.
2.2.3.3 Joint Powers

Joint power can be calculated as the product of the joint moment and the joint angular velocity. Bezodis et al. (2008) assessed the ankle, knee and hip joint powers during the stance phase of maximum velocity sprinting. The ankle was found to dissipate power through the first half of stance and then generated power for the remainder of stance, however, the amount of power dissipation exceeds power generation so the ankle acts as a net power dissipater. The knee was found to fluctuate between a power generator and dissipater and thus is seen to adopt a compensatory role. The hip was found to generate power throughout the majority of stance, which is followed by power dissipation and thus the hip acts as a net power generator.

2.2.3.4 Joint Stiffness

Joint stiffness is typically calculated as the change in the joint moment divided by the change in joint angle during the braking phase or the slope of the joint moment-joint angle curve (Stefanyshyn and Nigg. 1998; Kuitunen et al. 2002). Stefanyshyn and Nigg (1998) compared the moment-angle relationship of the ankle joint in running and sprinting in competitive male and found significantly higher ankle joint stiffness in sprinting compared to running. Kuitunen et al. (2002) assessed joint and knee stiffness over a range of sprint velocities (70, 80, 90 and 100% of maximum velocity). Shorter contact times were associated with higher levels of ankle stiffness ($r = -0.81$) over all sprint conditions. Furthermore, ankle stiffness did not change significantly between any of the sprint conditions whereas knee stiffness increased significantly as the sprinting velocity increased. This suggests that, in sprinting, the spring like behaviour of the stance leg might be adjusted through the regulation of the knee joint however considerable individual variation exists (Kuitunen et al. 2002). In contrast, Nagahara and Zushi (2017) found that increases in maximum velocity, in a group of well-trained male sprinters after six months of winter training, were achieved via longer step lengths, which were accompanied by increased vertical stiffness, ankle stiffness and reduced dorsiflexion with no changes found in knee stiffness. Higher levels of ankle stiffness would facilitate the transmission of larger forces into the ground during very short stance phases (~0.100 s) and thus enable longer step lengths (Nagahara and Zushi, 2017).
2.3 The Relationship between Sprint Performance, Maximum Strength and Reactive Strength

2.3.1 Maximum Strength

Maximum strength has been defined as the ability to voluntarily generate maximal force at very low velocities (Sale and Norman 1991) or alternatively as the highest force capability of the neuromuscular system during slow, eccentric, concentric or isometric contractions (Newton and Dugan 2002). Maximum strength can be assessed using both isometric and dynamic methods (Newton and Dugan 2002). Isometric tests require the athlete to adopt a set position and then apply force maximally against a fixed constraint with the maximum force produced considered to be representative of the athlete’s maximum strength (Newton and Dugan 2002). Isometric squats and isometric mid-thigh pulls are two commonly performed isometric tests (Brady et al. 2018). In an isometric squat test, the athlete adopts a squatting position with a pre-determined knee angle e.g. 120º (Young et al. 1995) whereas in an isometric midthigh pull an athlete adopts the second pull position of the clean with an upright trunk and a knee angle ~130-140º (Stone et al. 2004; Haff et al. 2005). Dynamic tests typically involve the determination of an athlete’s one repetition maximum (1 RM) i.e. the maximum load that can be lifted in kg, in a lower body task such as the back squat or deadlift (Newton and Dugan 2002). The literature assessing the relationship between maximum strength and sprint performance in sprint athletes is summarised below.

Young et al. (1995) assessed the relationship between maximum strength, measured in an isometric squat and speed measures taken during a 50 m sprint from a block start in Australian junior male (n=11) and female (n=9) sprinters. A very strong negative correlation was found between peak force in the isometric squat and the fastest 10 m split ($r = -0.79$).

Meckel et al. (1995) assessed the relationship between maximum strength, measured as 1 RM back squat relative to body mass, and 100 m sprint time in 30 female sprinters. A very strong negative correlation was found between back squat 1 RM relative to body mass and 100 m sprint time ($r = -0.89$).

Bret et al. (2002) assessed the relationship between the maximum force produced in a back squat relative to body mass and speed measures recorded over 100 m in 19 male sprinters (100 m PB: 11.43 ± 0.60 s). The maximum force relative to body mass had a very strong
positive correlation with the mean velocity over 0-30 m ($r = 0.61$), 30-60 m ($r = 0.68$), 60-100 m ($r = 0.68$) and 0-100 m ($r = 0.75$).

Requena et al. (2011) assessed the relationship between 1 RM back squat and sprint time measured over 10, 20, 30, 40, 60 and 80 m in 21 semi-professional 100 or 200 m sprint specialists. Significant moderate to strong negative correlations were found between the absolute 1 RM and sprint times over 30, 40, 60 and 80 m ($r = -0.54$ to -0.46). When the 1 RM back squat was expressed relative to body mass significant moderate to large negative correlations were found for all sprint measures ($r = -0.59$ to -0.49).

Okkonen and Hakkinen (2013) assessed the relationship between 1 RM back squat and sprint time measured over 10 m from a block start in nine male athletes: four sprinters, one decathlete, one long jumper and one triple jumper. Significant very strong negative correlations were found between 10 m time and the peak resultant force relative to body mass in the squat ($r = -0.74$) and the squat 1 RM relative to body mass ($r = -0.81$).

Combining the five summarised studies, maximum strength was measured using four distinct squat measures: peak force in an isometric squat, back squat 1 RM, back squat 1 RM relative to body mass and peak force in a back squat relative to body mass. Four of the studies used relative measures of strength and two studies used absolute measures of strength. Moderate to very strong relationships were found over sprint distances ranging from 10 m to 100 m and mean velocities for the acceleration phase (0-30 m), maximum velocity phase (30-60 m) and the deceleration phase (60-100 m). The extant literature has focused only on performance outcomes whereas the relationship between maximum strength and sprint kinematic or kinetic variables has yet to be assessed.

### 2.3.2 Reactive Strength

Reactive strength has been defined as an athlete’s capacity to bear a stretch load and subsequently switch rapidly from an eccentric to concentric muscle action (Newton and Dugan 2002) or alternatively an athlete’s ability to rapidly generate force under high eccentric loads (Lockie et al. 2015). Reactive strength is assessed in movements that utilise the stretch shortening cycle (SSC). The SSC is characterised by a lengthening or eccentric muscle contraction quickly followed by a shortening or concentric muscle contraction (Nicol et al. 2006). SSCs have been classified as fast or slow based on the ground contact times (CTs) with CTs < 0.250 s considered fast and CTs > 0.250 s considered slow
(Schmidtbleicher 1992). Sprinting is considered a fast SSC activity as every step has a CT < 0.250 s. Furthermore, sprinting requires the ability to tolerate high impact forces and generate as much force as possible to propel the athlete vertically and horizontally within very short time periods (Weyand et al. 2000; Clark and Weyand 2014). Therefore, reactive strength should logically be an important strength quality for sprinters.

Reactive strength is typically assessed in fast SSC movements such as drop jumps, rebound jumps and ankle jumps or bilateral hopping. In a drop jump, athletes step off of a box, with a predetermined height, and immediately perform a single vertical jump (Young et al. 1995). In a rebound jump, athletes perform an initial vertical jump and upon landing they perform several continuous vertical jumps similar to the drop jump. Ankle jumps are performed similarly to rebound jumps however the athletes are instructed to keep their legs as straight as possible so to limit the involvement of the knee joint. Reactive strength has generally been assessed using the reactive strength index (RSI) which can be calculated by dividing the jump height or flight time in a drop jump, rebound jump or ankle jump by the contact time (Young 1995; Newton and Dugan 2002; Nagahara et al. 2014). The literature assessing the relationship between reactive strength, assessed using the RSI, and sprint performance in sprint athletes is summarised below.

Young et al. (1995) assessed the relationship between drop jump RSI, measured using 0.30, 0.45, 0.60 and 0.75 m box heights, and 2.5 m sprint time and maximum velocity achieved during a 50 m sprint from a block start in Australian junior male (n=11) and female (n=9) sprinters. No significant correlations were found between any of the RSI measures and any of the sprint measures.

Hennessy and Kilty (2001) assessed the correlation between drop RSI, from a 0.3 m box, and 30, 100 and 300 m sprint time in 17 nationally ranked female completive sprinters. A very strong negative correlation was found between drop jump RSI, 30 m sprint time (r = -0.79) and 100 m time (r = -0.75) only.

Smirnitou et al. (2008) assessed the correlation between drop RSI, from a 0.4 m, and sprint measures recorded in a 100 m sprint in 25 male regional level sprinters (100 m PB = 11.71 ± 0.53 s). Significant moderate to large negative correlations were found between drop jump RSI and sprint time over 10, 30, 60 and 100 m (r = -0.57 to -0.49) and average velocity over 0-10, 30-60, and 60-100 m (r = 0.49 to 0.53).
Nagahara et al. (2014) assessed the correlation between reactive strength measured in rebound jumps and ankle jumps with sprint measures taken recorded during a 60 m sprint in 19 male sprinters (100 m PB: 10.72 to 11.79 s). A significant moderate negative relationship was found between RSI measured in the ankle jump and 60 m sprint time \((r = -0.49)\) and moderate to large positive correlations were found between ankle jump RSI and step acceleration from the 14th to 19th step (23 to 33 m) \((r = 0.48\) to 0.54). The correlation between rebound jump RSI and 60 m sprint and step accelerations were not significant.

Kariyama and Zushi (2016) assessed the correlation between reactive strength measured in rebound jumps and maximum sprint velocity in a 60 m sprint in 16 male sprinters. There was no significant correlation between rebound jump reactive strength and maximum sprint velocity \((r = 0.295, p = 0.288)\).

Loturco et al. (2017) assessed the correlation between drop jump RSI, measured from 0.45 and 0.75 m box heights, and sprint measures recorded during a 60 m sprint in male \((n = 12)\) and female \((n = 7)\) track athletes. No significant correlations were found between the 0.45 and 0.75 m drop jump RSI and any of the sprint measures. Additionally, Loturco et al. (2017) compared RSI and sprint times between male and female athletes. Although the male athletes had quicker sprint times (large to extremely large effects) there were no differences between groups in RSI.

Combining the six summarised studies, reactive strength was measured using drop jumps in four studies, rebound jumps in two studies and ankle jumps in one study. In the studies using drop jumps, box heights of 0.30 and 0.75 m were used in two studies and box heights of 0.40 and 0.45 m were used in one study each. No significant relationships were found in any of the studies between reactive strength measured in rebound jumps and sprint performance. The studies using drop jumps had mixed results; two studies, using box heights ranging from 0.30 to 0.75 m, found no significant correlation with sprint performance (sprint time over 2.5, 10, 20, 40 and 60 m and maximum velocity) whereas two other studies, using 0.30 and 0.40 m box heights, found moderate to very large negative correlations with sprint performance (sprint time over 10, 30, 60 and 100 m and maximum velocity). Shorter contact times are typically observed in drop jumps from lower box heights (0.3 and 0.4 m) compared to higher box heights (≥0.60 m) (Beattie et al. 2017) and therefore may be more appropriate as indicators of reactive strength in sprinters. The contact times achieved during the ankle jumps...
(0.132 ± 0.008 s) in the study by Nagahara et al. (2014) were lower than the contact times typically observed during drop and rebound jumps (CT range: 0.150 to 0.414 s). Consequently, the role of reactive strength using drop jumps from low drop heights and ankle jumps merits additional investigation in sprint athletes.

2.4 Effects of Resistance Training on Sprint Athletes

Training transfer is a key concern to sprint coaches when designing resistance training programmes. Transfer refers to how well the gains in training carry over to sprint performance (Young 2006). An athlete’s preparation time is limited and therefore making training as effective as possible i.e. maximising the transfer from training to performance, is of significant importance. Sprint training has direct transfer to sprint performance and consequently, sprint training is the most important type of training for sprint athletes. However, negative outcomes such as overtraining, muscle imbalances, injury risk and athlete boredom are possible if only sprint training is performed (Young 2006; Issurin 2013). Consequently, alternative training methods such as resistance training are required.

Although a considerable amount of research in sprint athletes has focused on the association between strength qualities and sprint performance, correlational work cannot infer causation and consequently, resistance training interventions on sprinters are required to assess the potential transfer of training. Such studies are in short supply however as longitudinal controlled trials on sprinters are difficult to perform due to the lack of availability of sprint athletes and the individual nature of the sport making standardising training difficult (Bolger et al. 2015). Despite these difficulties several interventions have been performed using a mixture of training methods and exercises.

2.4.1 Description of Resistance Training Exercises

Resistance training can typically be performed using traditional exercises, ballistic exercises, plyometric exercises and resisted sprinting. Traditional exercises are characterised by the acceleration of a load, typically a barbell, followed by the deceleration of the load at the end of the range of motion (Cormie et al. 2011). Traditional exercises, such as the back squat and deadlift, can be overloaded by increasing the load to be lifted or increasing the velocity, intended or actual, of the lift (Cormie et al. 2011). Conversely, in ballistic exercises the load is accelerated, as explosively as possible, throughout the entire range of motion to the point at
which the barbell is released or the athlete leaves the ground e.g. jump squats and high pulls (Cormie et al. 2008).

Plyometric exercises utilise a rapid stretch shortening cycle action where an eccentric muscle action is coupled with a concentric muscle action (Nicol et al. 2006). Plyometric exercises can be performed unilaterally or bilaterally, vertically or horizontally, and are distinct from ballistic exercises as they are typically performed with no additional load. Overload is generally achieved by reducing the duration of the stretch shortening cycle (Smith et al. 2011) or by increasing the stretch load (Cormie et al. 2011; Cappa and Behm 2013). Resisted sprinting is performed by applying external resistance e.g. a weighted sled or parachute, to an athlete when they are sprinting (Petrakos et al. 2016). An external overload beyond that of resisted sprinting is caused by the mass of the sled and the coefficient of friction between the ground and the sled or the size of the parachute used (Martinopoulou et al. 2011; Petrakos et al. 2016).

2.3.2 Summary of Resistance Training Interventions on Sprint Athletes

Blazevich and Jenkins (2002) assessed the effects of seven weeks of high (n = 5) and low velocity (n = 4) lower body resistance training on sprint performance in elite male junior sprinters (100 m PB: 10.89 ± 0.21 s). Lower body resistance training was completed twice a week in conjunction with the athlete’s standard sprint training and two upper body training sessions involving the bench press, bent-over row, lateral raises, dips, pull-downs and abdominal exercises performed for three sets of 10 repetitions at 10 RM load. The lower body resistance training consisted of squats performed to 90°, hip extension, leg extension, hip flexion and leg flexion performed using a pin weighted machine. Loads of 30-50% of 1 RM were used in the high velocity training and athletes were instructed to perform the concentric phases of the lifts as quickly as possible. Loads of 70-90% of 1 RM were used in the low velocity training and athletes were instructed to try to move the load as quickly as possible during the concentric phase with heavy load causing a reduction in the velocity of the lift. There were no significant differences between pre and post-test scores for either training group in 20 m sprint time from a standing start or from a flying start, 1 RM squat, hip flexion and hip extension performed at 1.05, 4.74 and 8.42 rad·s⁻¹. When groups were combined, significant improvements in 20 m sprint times from a standing start, 1 RM back squat and hip extension torque at 1.05 rad·s⁻¹ were found.
Satkunskiene et al. (2009) assessed the effects of eight weeks of power training on maximum sprint velocity and sprint kinematics during a 40 m sprint in seven male sprinters (60 m PB: 6.77 – 7.51 s). The power training was performed three times a week and consisted of four weeks of power endurance training and a further four weeks of power training. The power endurance training consisted of plyometric exercises such as hurdle jumps, standing vertical jumps as well as repeated hops and runs performed upstairs, in place and up hills. All exercises were performed at 60-90% of maximum intensity for 20 s for 5-10 repetitions with 30-60 s passive rest between exercises. The power training consisted of plyometric exercises such as depth jumps and repeated hops and jumps, resisted sprints and free sprints from blocks, dynamic exercises such as seated calf raises, back extensions, leg curls and pec deck butterflys performed at 100% intensity for 10 s for 5-7 repetitions with 3-5 minutes of passive rest. A significant difference was found in the maximum thigh angle during swing (-5.53%) only. A 3.3% increase in maximum velocity was found however this was not significant (p = 0.08).

Martinopoulou et al. (2011) compared the effects of 4 weeks of resisted sprint training (n = 8) to unresisted sprint training (n = 8) on acceleration and maximum velocity in male sprint athletes. The resisted sprint training was performed using a large sprint parachute resulting in a 10% decrease in sprint velocity. Resisted and unresisted sprinting sessions were completed three times a week. Sprint sessions consisted of 4 x 30 m and 4 x 50 m sprints with 4 and 6 minutes of rest given between repetitions respectively and 10 minutes of rest given between sprint distances. Significant improvements in the resisted sprint group were found in the acceleration phase for step length (5.56%), sprint time and sprint velocity over 0-10 m (-3.44% and 3.29%), 10-20 m (-2.33% and 2.72%) and 0-20 m (-3.29% and 3.34%). Significant improvements in the resisted sprint group were also found in the maximum velocity phase for step frequency (4.56%), flight time (-9.16%), 40-46 m sprint velocity (2.29%) and for 40-50 m sprint time (-3.2%) and sprint velocity (3.49%). Significant improvements in the unresisted sprint group were found in the acceleration phase for sprint time and sprint velocity over 0-20 m (-1.96% and 1.83%). No significant differences were found in the unresisted sprint group for the maximum velocity phase.

Alcaraz et al. (2014) assessed the effects of four weeks of resisted sprinting training with sled towing (n = 6 men, n = 5 women) compared to unresisted sprint training (n = 8 men, n = 3 women) on 50 m sprint performance. Male participants had a 100 m PB between 10.5 and
11.5 s and female participants had a 100 m PB between 12.0 and 13.0 s. The resisted sprint training group performed all sprints using a weighted sled resulting in a 7.5% decrease in sprint velocity. Two sprint sessions were performed a week with sessions consisting of 50 m sprints, flying sprints over 20 and 30 m and sprint bounding over 30 m. Additionally, all athletes completed two weekly resistance training sessions using upper and lower body exercises and loads of 75-85% of 1 RM. Significant differences between pre and post-test were found in the resisted sprint group for 15-30 m velocity (2.36%) whereas significant differences were found in 30-50 m velocity (1.86%) in the unresisted group.

Kamandulis et al. (2012) assessed the effects of three weeks of power endurance training followed by four weeks of high intensity power training on 60 sprint time in seven Lithuanian national team sprinters (100 m PB: 10.81 ± 0.22). The power endurance training consisted of plyometric exercises such as hurdle jumps, stair jumps and vertical jumps, and sprints alternated with slow jogging. All exercises were performed at 60-90% of maximum intensity for 20 s for 5-10 repetitions with 30-60 s rest between exercises. The high intensity power training consisted of plyometric exercises such as hurdle jumps, stair jumps and vertical jumps, dynamic exercises using inertial loads for the plantarflexors, chest and back extensors performed at 95-100% of maximum intensity and sprints performed from a crouch start and with resistance. Significant improvements were found in the knee extensors’ isometric maximum voluntary contraction (MVC) torque (7.4%), drop jump height (3.5%), countermovement jump height (8.7%) and 60 m sprint time (-1.8%).

Balsolobre-Fernandez et al. (2013) assessed the effects of ten weeks of power training on sprint acceleration in seven national and international level 400 m hurdlers. The power training consisted of two sessions a week of five sets of eight jump squats performed at a load that maximised power output. Significant improvements were found in 1 RM squat (7.9%), squat jump flight time (2.3%), the percentage of 1 RM in which maximum power was produced (11%) and 30 m sprint time (-1.43%). No significant differences were found in countermovement jump flight time or the maximum power output.

Combining the six summarised studies, traditional exercises were utilised in four, resisted sprinting was used in four, plyometric exercises were utilised in three and ballistic exercises were only used in one. Five of the six studies assessed male sprinters only whereas the remaining study by Alcaraz et al. (2014) assessed both male and female sprinters. The
duration of the interventions also varied. Two of the interventions were performed over four weeks, one over seven weeks, two over eight weeks and the longest intervention was performed over 10 weeks. Very small sample sizes were used with four of the six studies containing seven or fewer subjects and no study containing more than 11 subjects. The risk of making a type 2 error i.e. concluding that there is no effect when there is one, due to insufficient statistical power is high when small sample sizes are used. However, despite the small sample sizes, significant improvements were found in sprint performance, sprint time or sprint velocity, in five out of the six studies with the remaining study by Satkunskiene et al. (2009) reporting a 3.3% increase in maximum velocity however this was not significant (p = 0.08). Additionally, two of the six studies also assessed step kinematics with ground contact time, flight time, step length and step frequency assessed by Satkunskiene et al. (2009) and Martinopoulou et al. (2011). Only Martinopoulou et al. (2011) found significant improvements in step length (acceleration phase) and step frequency and flight time (maximum velocity phase).

Improvements in sprint time, sprint velocity and step kinematics were achieved over sprint distances ranging from 20 to 60 m. However, there are several limitations that must be acknowledged in order to accurately assess the effects of resistance training interventions on sprint performance. Four of the six studies had no sprint control group where the sprinters performed their regular sprint training only. Consequently, it is not known whether the sprint training that the athletes completed, in addition to the intervention resistance training, was fully responsible or in some part responsible for the reported improvements in sprint performance. Martinopoulou et al. (2011) and Alcaraz et al. (2014) included a sprint only control group and both studies reported beneficial effects from resisted sprinting however significant improvements in sprint performance were also seen in the unresisted sprint training groups. Additionally, three of the six interventions combined at least three resistance training methods incorporating a range of exercises, which limits the ability to attribute performance improvements to any one specific training modality.

2.5 Biomechanical Comparisons Between Sprinting and Resistance Training Exercises

The previous section introduced the concept of training transfer and outlined the literature assessing the effects of resistance training on sprint performance in sprinters. A fundamental principle of exercise prescription, related to transfer, is the specific adaptation to imposed
demands (SAID) or specificity. According to this principle, the training stimulus / stress applied dictate the subsequent adaptation that occurs (Young 2006; Haff and Triplett 2016). From a biomechanical perspective, specificity can refer to the muscles activated, the movement kinetics i.e. the magnitude of force produced and the direction of force application, the movement kinematics i.e. joint angles, movement velocity, and the type of muscle action i.e. isometric, concentric and eccentric (Haff and Triplett 2016). Resistance training exercises do not have to be identical to sprinting in all aspects but they must provide the necessary overload to illicit the desired performance adaptation. Several studies have been conducted assessing the potential specificity of resistance training exercises with sprint performance; these studies are summarised below.

2.5.1 Summary of Studies Comparing Sprinting and Resistance Training Exercises

Mero and Komi (1994) compared maximal velocity sprinting to maximal bounding, maximal stepping and maximal hopping on the right and left legs in seven male sprinters. In maximal bounding the subjects’ ball of the foot made contact with the ground first whereas in the maximal stepping and hopping the heel made first contact with the ground. All exercises were performed at maximum speed. A summary of the biomechanical measures assessed and key findings are outlined in Table 2.1. The authors concluded that maximal bounding could be considered a specific strength exercises for sprinters due to the short contact times (bounding: 0.120 ± 0.007 s versus sprinting: 0.101 ± 0.010 s) and comparable average horizontal propulsive forces (bounding: 354 ± 67 N versus sprinting: 338 ± 58 N) to sprinting. The authors also concluded that maximal hopping and stepping may be effective at developing the leg extensor muscles to sustain impact forces as the average vertical forces were 1.64-1.93 higher in stepping and hopping compared to maximum velocity sprinting.

Okkonen and Hakkinen (2013) compared the block phase of the sprint start with sled pulls, countermovement jumps, and half squats in nine male athletes: four sprinters, one decathlete, one long jumper and one triple jumper. Sled pulls were performed over 10 m using loads of 10 and 20% of body mass. Countermovement jumps were performed with no added resistance and with loads 10 and 20% of body mass. The half squats were performed at a load of 70% of 1 RM and at 1 RM load. A summary of the biomechanical measures assessed and key findings are outlined in Table 2.1. All measures were collected during the concentric phase of the movements only. The authors concluded that the exercises most likely to induce
positive changes, of the exercises studied, in sprinting were sled pulling due to the kinematic similarity and countermovement jumps due to the higher angular velocities.

Kariyama and Zushi (2016) compared maximal velocity sprinting to rebound jumps in 16 male sprinters. One trial of rebound jumps consisted of participants performing five repeated vertical jumps using a double-leg takeoff with the aim of jumping as high as possible while also attempting to minimise contact time. A summary of the biomechanical measures assessed and key findings are outlined in Table 2.1. The authors concluded that rebound jumps may be useful, as a plyometric exercise for sprinting, for improving mechanical output during the latter part of the support phase due to the existence of mechanical similarities. Mechanical similarities, assessed through positive correlations, were found in the ankle and knee joint kinetics i.e. average torque in eccentric and concentric phases and average negative power.

The existing literature has compared the biomechanics of twelve exercises in terms of their potential suitability for sprinting. Of the twelve exercises, eight were plyometric exercises, two were variations of resisted sprinting and two were traditional exercises. Seven exercises were compared to the sprint start whereas the remaining five exercises, all plyometric, were compared to maximum velocity sprinting. All exercises except for the two traditional exercises were considered potentially effective for improving sprint performance. The rationale for considering an exercise effective differed between studies.

Two studies argued that a lack of statistically significant differences was evidence of similarity in the movement patterns and thus considered the exercises kinematically (contact times and joint angles) or kinetically similar (vertical and horizontal force and power) and therefore specific to sprinting (Mero and Komi 1994; Okkonen and Hakkinen 2013). Furthermore, both Mero and Komi (1994) and Okkonen and Hakkinen (2013) argued that statistically significant differences in kinematic (angular velocity) or kinetic measures (vertical force) could also indicate that an exercise was effective for sprinting as they imposed demands greater than those observed in sprinting. In contrast, Kariyama and Zushi (2016) argued that positive correlations between sprinting and rebound jump kinetic measures, eccentric and concentric phase joint torque and the positive and negative joint power, demonstrated biomechanical similarity and thus rebound jumps could be considered a sprint specific exercise.
Table 2.1: Summary of studies comparing resistance training exercises to sprinting.

<table>
<thead>
<tr>
<th>Sprint Phase Assessed</th>
<th>Biomechanical Measures</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Velocity Mero and Komi (1994)</td>
<td>Horizontal Velocity (v)</td>
<td>Maximal Bounding</td>
</tr>
<tr>
<td>Sprint Phase Assessed</td>
<td>Stride Length (SL) and Stride Frequency (SF)</td>
<td>↓v, ↑SL, ↓SF, ↓FT, ↑CT</td>
</tr>
<tr>
<td>Flight Time (FT) and Contact Time (CT)</td>
<td>Braking Time (BT) and Propulsion Time (PT)</td>
<td>↓FH, ↓PF</td>
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<tr>
<td>Braking Time (BT) and Propulsion Time (PT)</td>
<td>Average Horizontal and Vertical Braking Force (FH and FV)</td>
<td>Maximal Stepping</td>
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<tr>
<td>Average Horizontal and Vertical Braking Force</td>
<td></td>
<td>↓v, ↑SL, ↓SF, ↓FT, ↑CT, ↑BT, ↑PT</td>
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<tr>
<td>Average Horizontal and Vertical Propulsion Force (FHV and FVH)</td>
<td></td>
<td>Maximal Hopping (Right Leg)</td>
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<tr>
<td>Average Resultant Force in Braking and Propulsion Phase (FR and FHR)</td>
<td></td>
<td>↓v, ↑SL, ↓SF, ↓FT, ↑CT, ↑BT, ↑PT</td>
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<tr>
<td>Horizontal and Vertical Braking Impulse (IH and IV)</td>
<td></td>
<td>Maximal Hopping (Left Leg)</td>
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<tr>
<td>Horizontal and Vertical Propulsion Impulse (IH and IV)</td>
<td></td>
<td>↓v, ↑SL, ↓SF, ↓FT, ↑CT, ↑BT, ↑PT</td>
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<tr>
<td>Horizontal Braking and Propulsive Power Output</td>
<td></td>
<td>Maximal Hopping (Right Leg)</td>
</tr>
<tr>
<td>Resultant Force Direction in Braking and Propulsion Phase (FDir and FR)</td>
<td></td>
<td>↓v, ↑SL, ↓SF, ↓FT, ↑CT, ↑BT, ↑PT</td>
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<tr>
<td>Gastrocnemius Average EMG (GASM)</td>
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<tr>
<td>Vastus Lateralis Average EMG (VL EMG)</td>
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<td>Biceps Femoris Average EMG (BF EMG)</td>
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<td>Gluteus Maximus Average EMG (GM EMG)</td>
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<td>Rectus Femoris Average EMG (RF EMG)</td>
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<tr>
<td>Sprint Phase Assessed</td>
<td>Biomechanical Measures</td>
<td>Findings</td>
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<tr>
<td>Block phase of Sprint Start</td>
<td>Force Production Time (FPT)</td>
<td>↑FPT, ↑RI, ↑GM&lt;sub&gt;EMG&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinAnk&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinKnee&lt;/sub&gt;, ↑Θ&lt;sub&gt;MaxKnee&lt;/sub&gt;</td>
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<td></td>
<td>Resultant Peak Force (RPF)</td>
<td>↑GM&lt;sub&gt;EMG&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinAnk&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinKnee&lt;/sub&gt;, ↑Θ&lt;sub&gt;MaxKnee&lt;/sub&gt;</td>
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<td></td>
<td>Resultant Impulse (RI)</td>
<td>↑Θ&lt;sub&gt;PeakAnk&lt;/sub&gt;, ↓Θ&lt;sub&gt;MeanAnk&lt;/sub&gt;, ↓Θ&lt;sub&gt;PeakKnee&lt;/sub&gt;, ↓Θ&lt;sub&gt;MeanKnee&lt;/sub&gt;, ↓Θ&lt;sub&gt;PeakHip&lt;/sub&gt;</td>
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<tr>
<td>Okkonen and Hakkinen (2013)</td>
<td>Resultant Takeoff Velocity (v&lt;sub&gt;TO&lt;/sub&gt;)</td>
<td>↑FPT, ↑RI</td>
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<td></td>
<td>Gluteus Maximus Average EMG (GM&lt;sub&gt;EMG&lt;/sub&gt;)</td>
<td>↑RI, ↑GM&lt;sub&gt;EMG&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinAnk&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinKnee&lt;/sub&gt;, ↑Θ&lt;sub&gt;MaxKnee&lt;/sub&gt;</td>
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<td></td>
<td>Biceps Femoris Average EMG (BF&lt;sub&gt;EMG&lt;/sub&gt;)</td>
<td>↑RI, ↑GM&lt;sub&gt;EMG&lt;/sub&gt;, ↑Θ&lt;sub&gt;MinAnk&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinKnee&lt;/sub&gt;, ↑Θ&lt;sub&gt;MaxKnee&lt;/sub&gt;</td>
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<td></td>
<td>Vastus Lateralis Average EMG (VL&lt;sub&gt;EMG&lt;/sub&gt;)</td>
<td>↑RI, ↑GM&lt;sub&gt;EMG&lt;/sub&gt;, ↑Θ&lt;sub&gt;MinAnk&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinKnee&lt;/sub&gt;, ↑Θ&lt;sub&gt;MaxKnee&lt;/sub&gt;</td>
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<td>Ankle Angle (Θ&lt;sub&gt;MinAnk&lt;/sub&gt; and Θ&lt;sub&gt;MaxAnk&lt;/sub&gt;)</td>
<td>↑RI, ↑GM&lt;sub&gt;EMG&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinAnk&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinKnee&lt;/sub&gt;, ↑Θ&lt;sub&gt;MaxKnee&lt;/sub&gt;</td>
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<td></td>
<td>Knee Angle (Θ&lt;sub&gt;MinKnee&lt;/sub&gt; and Θ&lt;sub&gt;MaxKnee&lt;/sub&gt;)</td>
<td>↑RI, ↑GM&lt;sub&gt;EMG&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinAnk&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinKnee&lt;/sub&gt;, ↑Θ&lt;sub&gt;MaxKnee&lt;/sub&gt;</td>
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<td>Hip Angle (Θ&lt;sub&gt;MinHip&lt;/sub&gt; and Θ&lt;sub&gt;MaxHip&lt;/sub&gt;)</td>
<td>↑RI, ↑GM&lt;sub&gt;EMG&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinAnk&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinKnee&lt;/sub&gt;, ↑Θ&lt;sub&gt;MaxKnee&lt;/sub&gt;</td>
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<td>Peak and Average Ankle Angular Velocity (ω&lt;sub&gt;PeakAnk&lt;/sub&gt; and ω&lt;sub&gt;MeanAnk&lt;/sub&gt;)</td>
<td>↑RI, ↑GM&lt;sub&gt;EMG&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinAnk&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinKnee&lt;/sub&gt;, ↑Θ&lt;sub&gt;MaxKnee&lt;/sub&gt;</td>
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<td>Peak and Average Knee Angular Velocity (ω&lt;sub&gt;PeakKnee&lt;/sub&gt; and ω&lt;sub&gt;MeanKnee&lt;/sub&gt;)</td>
<td>↑RI, ↑GM&lt;sub&gt;EMG&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinAnk&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinKnee&lt;/sub&gt;, ↑Θ&lt;sub&gt;MaxKnee&lt;/sub&gt;</td>
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<td>Peak and Average Hip Angular Velocity (ω&lt;sub&gt;PeakHip&lt;/sub&gt; and ω&lt;sub&gt;MeanHip&lt;/sub&gt;)</td>
<td>↑RI, ↑GM&lt;sub&gt;EMG&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinAnk&lt;/sub&gt;, ↓Θ&lt;sub&gt;MinKnee&lt;/sub&gt;, ↑Θ&lt;sub&gt;MaxKnee&lt;/sub&gt;</td>
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</table>

| Sled Pull (10% BM Load) | ↑FPT, ↑RI, ↑GM<sub>EMG</sub>, ↓Θ<sub>MinAnk</sub>, ↓Θ<sub>MinKnee</sub>, ↑Θ<sub>MaxKnee</sub> |
| Sled Pull (20% BM Load) | ↑FPT, ↑RI, ↑GM<sub>EMG</sub>, ↑Θ<sub>MinAnk</sub>, ↑Θ<sub>MinKnee</sub>, ↑Θ<sub>MaxKnee</sub> |
| CMJ                    | ↑FPT, ↑RI, ↑GM<sub>EMG</sub>, ↓Θ<sub>MinAnk</sub>, ↓Θ<sub>MinKnee</sub>, ↑Θ<sub>MaxKnee</sub> |
| CMJ (10% BM Load)      | ↑FPT, ↑RI, ↑GM<sub>EMG</sub>, ↓Θ<sub>MinAnk</sub>, ↓Θ<sub>MinKnee</sub>, ↑Θ<sub>MaxKnee</sub> |
| CMJ (20% BM Load)      | ↑FPT, ↑RI, ↑GM<sub>EMG</sub>, ↓Θ<sub>MinAnk</sub>, ↓Θ<sub>MinKnee</sub>, ↑Θ<sub>MaxKnee</sub> |
| Half Squat (70% of 1 RM) | ↑FPT, ↑RI, ↑GM<sub>EMG</sub>, ↓Θ<sub>MinAnk</sub>, ↓Θ<sub>MinKnee</sub>, ↑Θ<sub>MaxKnee</sub> |
**Half Squat (1 RM)**

↑FPT, ↑RPF, ↑GM$_{EMG}$, ↓BF$_{EMG}$

No angle or angular velocity data reported

<table>
<thead>
<tr>
<th>Sprint Phase Assessed</th>
<th>Biomechanical Measures</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Velocity</td>
<td>Concentric Phase Average Joint Torque ($\tau_{\text{AnkCon}}, \tau_{\text{KneeCon}}$ and $\tau_{\text{HipCon}}$)</td>
<td>Rebound Jump</td>
</tr>
<tr>
<td>Kariyama and Zushi</td>
<td>Eccentric Phase Average Joint Torque ($\tau_{\text{AnkEcc}}, \tau_{\text{KneeEcc}}$ and $\tau_{\text{HipEcc}}$)</td>
<td>Significant positive correlations found for $\tau_{\text{AnkCon}}, \tau_{\text{KneeCon}}$ and $\tau_{\text{KneeEcc}}$</td>
</tr>
<tr>
<td></td>
<td>Average positive joint power ($P_{\text{AnkPos}}, P_{\text{KneePos}}$ and $P_{\text{HipPos}}$)</td>
<td>Significant positive correlations found for $P_{\text{AnkNeg}}$ and $P_{\text{KneeNeg}}$</td>
</tr>
<tr>
<td></td>
<td>Average negative joint power ($P_{\text{AnkNeg}}$ and $P_{\text{KneeNeg}}$)</td>
<td>Similar patterns for ankle and knee joint angular velocity, joint torque and joint power.</td>
</tr>
<tr>
<td></td>
<td>Angular Velocity ($\omega_{\text{Ank}}, \omega_{\text{Knee}}$ and $\omega_{\text{Hip}}$)</td>
<td>Hip joint extension in sprinting only whereas hip joint flexion seen before extension in rebound jumps</td>
</tr>
</tbody>
</table>

↑ = significantly greater than sprinting; ↓ = significantly lower than sprinting
2.6 Chapter Summary

This chapter has provided a comprehensive description of the 100 m sprint phases and the biomechanics of maximum velocity sprinting. Furthermore, this chapter has reviewed the relevant literature on the effects of resistance training on sprint athletes and the biomechanical comparisons between sprinting and resistance training exercises. Finally, this chapter summarised the extant literature examining the relationship between sprint performance, maximum strength and reactive strength. Consequently, this review has identified the following questions that require further examination:

- What is the relative importance of each sprint phase to overall 100 m performance?
- What is the relationship between maximum strength and reactive strength with sprint performance and mechanical properties?
- What exercises are sprint coaches prescribing to their sprint athletes and why are those exercises selected?
- How suitable are the most commonly prescribed resistance training exercises for maximum velocity sprinting?
Chapter 3: Profiling Elite Male 100 M Sprint Performance: The Role of Maximum Velocity and Relative Acceleration.
3.1 Introduction

The 100 m sprint can be divided into three main phases: the acceleration phase which is sometimes sub-divided into initial acceleration phase and pick up phase, the maximum velocity phase, and the deceleration phase (Ae 1992; Mackala 2007; Schiffer 2009; Maćkała et al. 2015). Plotting a sprinter’s velocity-distance curve allows each distinct phase of the 100 m to be identified. Initial acceleration is represented by a rapid increase in velocity (Mackala 2007); whereas a more gradual increase in velocity (pick up phase) is subsequently observed (Maćkała et al. 2015; Manzer 2016). The maximum velocity phase is characterised by a gradual increase in velocity which is represented as a relatively flat section of the velocity-distance curve where the velocity remains at 95-100% of maximum velocity ($v_{max}$) (Seagrave et al. 2009). Sprinters typically reach their highest speed between 50 and 80 m with faster sprinters usually reaching $v_{max}$ later in the race (Volkov and Lapin 1979; Krzysztof and Mero 2013; Slawinski et al. 2017). During the deceleration phase, sprinters attempt to counteract the inevitable decrease in velocity due to fatigue and maintain the highest velocity possible for the remainder of the race (Slawinski et al. 2017). This is represented by a gradual decrease in velocity, usually over the final 20 m of the race, and can be assessed by calculating the percentage of velocity lost ($v_{Loss}$) relative to $v_{max}$ (Ryu et al. 2012).

A sprinter’s position-time and velocity-time curves can be modelled throughout the acceleration phase of a sprint using a mono-exponential function (Furusawa et al. 1927; Henry and Trafton 1951; Chelly and Denis 2001; Di Prampero et al. 2005). This function requires two input parameters: the sprinter’s maximal horizontal velocity ($v_{hmax}$) and the acceleration time constant ($\tau$) which is the ratio of $v_{hmax}$ to the initial horizontal acceleration (Chelly and Denis 2001). The variable $\tau$ represents the total time lost in overcoming inertia up to the point maximum velocity is achieved, (Furusawa et al. 1927) thus its unit is the second. For example, if a sprinter reached $v_{hmax}$ at 40 m during a sprint with a $\tau$ value of 1 s, this means that the sprinter would cover this 40 m distance 1 s faster if there were no lag due to inertia i.e. no acceleration phase. If $\tau$ were equal to zero, the sprinter would instantaneously reach maximal velocity without any acceleration phase, which is obviously not possible. Consequently, a more practical description, is that $\tau$ represents an athlete’s relative acceleration ability with lower values indicating the ability to reach a higher percentage of $v_{max}$ quicker, relative to athletes with a higher $\tau$ (Clark et al. 2017). Despite the identification
of $\tau$ as a performance factor in sprinting, the specific influence of $\tau$ on 100 m performance in elite male sprinters has yet to be determined.

Several methods exist for modelling horizontal position-time and velocity-time from split times using the mono-exponential function. Furusawa et al. (1927) reported a mean difference of 0.079 m between the raw position data of a sprinter, collected at 10 points during a 54.9 m (60 yards) sprint, and the position estimated by the mono-exponential function. Clark et al. (2017) demonstrated that three split times recorded at 9.1, 18.3 and 36.6 m, in NFL Combine athletes, could be used to generate accurate distance-time, velocity-time and velocity-distance curves over 36.6 m (40 yards) using the mono-exponential equation. Samozino et al. (2016) demonstrated the validity of a 5 split zone method, where timing gates were set up at 10, 15, 20, 30 and 40 m, to assess position-time and velocity-time curves in sprinters and subsequently used these data to model power and force properties. The work of Furusawa et al. (1927), Samozino et al. (2016) and Clark et al. (2017) demonstrate the ability of the mono-exponential function to accurately model position-time and velocity-time curves over short sprints (< 55 m). Consequently, a method that allows the accurate derivation of horizontal position-time and velocity-time curves during the acceleration phase of a 100 m sprint with the fewest possible number of split times would be of considerable benefit to sprint coaches and researchers alike.

The limited availability of large numbers of world class athletes is often a problem for researchers in elite sport. This is understandable, especially in the 100 m sprint, as elite athletes often train in small highly specialised groups, dispersed throughout the world, with sprint coaches that dedicate a significant amount of time and investment to provide a high quality coaching service. Using publicly available sprint data, usually in the form of sprint split times, collected at major events by independent researchers or IAAF accredited biomechanical research teams provides a potential solution to the limited availability problem. Online publicly available data sets have been widely used in 100 m sprint research to assess the impact of rule changes (Brosnan et al. 2017), the effects of wind speed (Gómez et al. 2013), age and sex differences in sprint mechanical properties (Slawinski et al. 2017) and reaction times (Tønnessen et al. 2013), stride kinematics (Krzysztof and Mero 2013), kinetics and energetics of world class performers (Arsac and Locatelli 2002; Taylor and Beneke 2012; Di Prampero et al. 2015). Consequently, examination of sprint acceleration and
velocity profiles using these data sources has the potential to improve understanding of world class sprint performance.

The primary aim of this study was to determine the accuracy of a four split time modelling method to generate velocity-time and velocity-distance variables in elite 100 m male sprinters using publicly available sprint data from major international sprint events. The secondary aim was to assess the roles of key sprint parameters: $v_{\text{max}}$, $\tau$ and $v_{\text{Loss}}$ with the 100 m sprint performance and subsequently, the role of $v_{\text{max}}$ in each phase of the 100 m sprint. Thirdly, this study aimed to assess $\tau$ as an indicator of a sprinter’s relative acceleration ability. Finally, this paper aimed to compare faster and slower sprinters using modelled and measured race variables.

3.2 Methods

3.2.1 Subjects
The data used in this study were obtained from online position-time records taken during major athletics competitions with 82 male sprint athletes included in the final analysis. Athletes were subsequently divided into tertiles to facilitate further analysis. Tertiles were selected based on 100 m time with the first and third tertile considered the faster and slower groups respectively. Mean ± SD 100 m time, anthropometric data and IAAF points (2017) were obtained for all sprinters, faster sprinters and slower sprinters, see Table 3.1.

Table 3.1: Descriptive statistics (Mean ± SD) for all (n=82), faster (n=28) and slower (n=28) sprinters.

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th>Faster</th>
<th>Slower</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 m Time (s)</td>
<td>10.17 ± 0.23</td>
<td>9.91 ± 0.10</td>
<td>10.43 ± 0.09</td>
</tr>
<tr>
<td>Range</td>
<td>9.58 to 10.59</td>
<td>9.58 to 10.02</td>
<td>10.27 to 10.59</td>
</tr>
<tr>
<td>Age (years)</td>
<td>25 ± 3</td>
<td>26 ± 4</td>
<td>24 ± 3</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.80 ± 0.06</td>
<td>1.81 ± 0.06</td>
<td>1.79 ± 0.06</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>77.1 ± 7.4</td>
<td>78.3 ± 6.6</td>
<td>76.1 ± 8.0</td>
</tr>
<tr>
<td>IAAF Points</td>
<td>1151 ± 78</td>
<td>1238 ± 35</td>
<td>1063 ± 28</td>
</tr>
</tbody>
</table>

3.2.2 Data Sources
Sprint data were available from IAAF accredited biomechanics projects and additional research published by research groups utilising video analysis In total, data were publicly available for eight world championships between 1987 and 2017 (Moravec et al. 1988; Ae
and three Olympic Games between 1988 and 2012 (Brüggemann and Glad 1990; Krzysztof and Mero 2013). Athletes were included in the analysis only if their entire 100 m data were available, either as 10 m or 20 m split times, and if their reaction time (RT) were available via IAAF approved start information systems. Additionally, video footage of each race was assessed by the primary investigator to ensure that each athlete included in the final analysis completed their 100 m sprint without sustaining an injury or intentionally slowing down before the finish line. Only the athlete’s best performance in all competitions was retained for analysis. The championships, methods employed, split times recorded and number of athletes retained for the final analysis are described in Table 3.2. These data were recorded using a mixture of high speed video measurements (sampling rates: 50 – 250 Hz) and laser analysis (sampling rates: 50 – 100 Hz) which have been demonstrated to yield comparable results (Arsac and Locatelli 2002; Harrison et al. 2005).

Table 3.2: Competition sources of sprint data, measurement methods employed and reported split time intervals.

<table>
<thead>
<tr>
<th>Competition</th>
<th>Measurement Method</th>
<th>Reported Splits (Number of Athletes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olympic Games Seoul 1988</td>
<td>Video Analysis</td>
<td>10 m (4)</td>
</tr>
<tr>
<td>World Championships Tokyo 1991</td>
<td>Video Analysis</td>
<td>10 m (6)</td>
</tr>
<tr>
<td>World Championships Athens 1997</td>
<td>Laser</td>
<td>10 m (4)</td>
</tr>
<tr>
<td>World Championships Seville 1999</td>
<td>Video Analysis</td>
<td>10 m (7)</td>
</tr>
<tr>
<td>World Championships Osaka 2007</td>
<td>Video Analysis</td>
<td>10 m (3)</td>
</tr>
<tr>
<td>World Championships Berlin 2009</td>
<td>Video Analysis &amp; Laser</td>
<td>20 m (49) 10 m (3)</td>
</tr>
<tr>
<td>World Championships London 2017</td>
<td>Video Analysis</td>
<td>10 m (6)</td>
</tr>
</tbody>
</table>

3.2.3 Data Analysis

To ensure consistency in the analysis all data were presented in 20 m split times so that 0-20, 20-40, 40-60, 60-80 and 80-100 m data were available for all athletes. The following variables were included in the final analysis based on these raw position-time data: reaction time (RT), 100 m sprint performance (excluding RT), 20 m split times expressed as raw times and as percentages of 100 m time, maximum velocity ($v_{\text{max}}$), and the average velocity
achieved over the 0-20 m and 20-40 m sections expressed as a percentage of $v_{\text{max}}$. The $v_{\text{max}}$ was calculated as 20 m divided by the fastest 20 m split time achieved in the race. Additionally, the $v_{\text{Loss}}$ was determined as an indicator of the athlete’s ability to maintain maximum velocity during the final 20 m of the race (Ryu et al. 2012). The $v_{\text{Loss}}$ was calculated as $v_{\text{max}}$ minus average velocity over the final phase of the race divided by maximum velocity multiplied by 100, or simply,

$$\frac{v_{\text{max}} - \left( \frac{20 \text{ m}}{80-100 \text{ m time}} \right)}{v_{\text{max}}} \times \frac{100}{1}.$$ 

The first four split times (minus RT), representing the acceleration phase of the 100 m sprint, were subsequently used to generate horizontal position of the centre of mass ($x_h$) versus time ($t$) curves for each athlete using a mono-exponential function (Samozino et al. 2016)

$$x_h(t) = v_{h\text{max}} \cdot \left( t + \tau \cdot e^{-\frac{t}{\tau}} \right) - v_{h\text{max}} \cdot \tau$$

Where $v_{h\text{max}}$ is the maximum velocity achieved, $t$ is the time and $\tau$ is the acceleration time constant. Using the equation above and the Microsoft Excel solver function, the best estimations for $\tau$ and $v_{h\text{max}}$ were calculated using a least squares approach between the raw position-time data and the modelled position-time data. The estimated $\tau$ values were retained for the final analysis whereas the estimated $v_{h\text{max}}$ values were used only to compare against the raw $v_{\text{max}}$ values which were retained for the final analysis.

Using the approximated values of $v_{h\text{max}}$ and $\tau$ the velocity of the athlete’s centre of mass versus time curves could be generated by differentiating equation 1 with respect to time using the equation:

$$v_h(t) = v_{h\text{max}} \cdot (1 - e^{-\frac{t}{\tau}})$$

The velocity achieved at 20 and 40 m was estimated for each athlete using the generated velocity-time curves and expressed as a percentage of $v_{\text{max}}$, similar to the work of Clark et al. (2017).
3.2.4 Statistical Analysis

The accuracy of the four-split time modelling technique was evaluated through several methods. Firstly, the four measured split times used to generate the model (20, 40, 60 and 80 m) were compared with modelled times (n = 82). Secondly, where available, measured split times at 10, 30, 50 and 70 m were compared with modelled times (n = 33). Finally, measured and modelled average velocities over 0-20 m, 20-40 m, 40-60 m and 60-80 m in addition to \( v_{\text{max}} \) values were compared (n = 82). Bland-Altman 95% limits of agreement (LOA) analysis (Bland and Altman 1986) and intraclass correlation coefficients (ICCs) (2,1) with 95% confidence intervals (CI) (Atkinson and Nevill 1998) were used to compare modelled and measured variables.

Normality of the data was assessed by plotting and visually inspecting the shape of the histograms for all variables and by using the Shapiro Wilks test with the alpha level set at \( p < 0.05 \). Differences in all sprint measures between faster and slower groups were assessed using independent samples t-tests. Cohen’s d effect sizes (ES) were calculated and were interpreted as trivial (ES < 0.2), small (0.2 ≥ ES < 0.6), moderate (0.6 ≥ ES < 1.2), large (1.2 ≥ ES < 2), very large (2 ≥ ES < 4), and extremely large (≥ 4) according to the scale proposed by Hopkins et al. (2009).

Relationships between measures were assessed using the Pearson correlation coefficient or Spearman’s rank correlation coefficient with 95% confidence intervals (CI). Partial correlations were used to assess the relationships between \( \tau \) and 100 m sprint performance and between \( v_{\text{Loss}} \) and 100 m sprint performance while controlling for \( v_{\text{max}} \). The strength of the correlations were evaluated as: trivial (0 – 0.09), small (0.1 – 0.29), moderate (0.3 – 0.49), large (0.5 – 0.69), very large (0.7 – 0.89), near perfect (0.9 – 0.99) and perfect (1) (Hopkins et al. 2009). All statistical analyses were completed using SPSS (Version 24.0, SPSS, Inc., IL, USA) using an alpha level of \( p < 0.05 \).

3.3 Results

The results of the comparison between measured and modelled variables are given in Table 3.3. All variables displayed excellent accuracy and close agreement with the raw measures (range of mean bias: -0.2 to 0.2% and range of ICCs: 0.935 to 0.999) except for 10 m time which had a mean bias of 1.6 ± 1.3% and an ICC of 0.600.
Table 3.3: Mean ± SD results, mean bias ± SD with 95% LOA and single measure intraclass correlation coefficient with 95% CI for measured and modelled sprint times and sprint velocities.

<table>
<thead>
<tr>
<th>Sprint Times</th>
<th>Measured</th>
<th>Modelled</th>
<th>Mean bias ± SD (95% LOA)</th>
<th>% Mean bias ± SD (95% LOA)</th>
<th>ICC (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 m (s)</td>
<td>1.752 ± 0.039</td>
<td>1.779 ± 0.030</td>
<td>0.028 ± 0.023 (-0.018 to 0.073)</td>
<td>1.6 ± 1.3 (-1.0 to 4.1)</td>
<td>0.600 (-0.044 to 0.846)</td>
</tr>
<tr>
<td>20 m (s)</td>
<td>2.817 ± 0.047</td>
<td>2.820 ± 0.047</td>
<td>0.002 ± 0.008 (-0.014 to 0.018)</td>
<td>0.1 ± 0.3 (-0.5 to 0.6)</td>
<td>0.985 (0.975 to 0.990)</td>
</tr>
<tr>
<td>30 m (s)</td>
<td>3.710 ± 0.050</td>
<td>3.709 ± 0.050</td>
<td>-0.001 ± 0.011 (-0.022 to 0.020)</td>
<td>0.0 ± 0.3 (-0.6 to 0.6)</td>
<td>0.977 (0.954 to 0.989)</td>
</tr>
<tr>
<td>40 m (s)</td>
<td>4.665 ± 0.080</td>
<td>4.663 ± 0.082</td>
<td>-0.002 ± 0.008 (-0.017 to 0.013)</td>
<td>-0.1 ± 0.2 (-0.4 to 0.3)</td>
<td>0.995 (0.993 to 0.997)</td>
</tr>
<tr>
<td>50 m (s)</td>
<td>5.467 ± 0.067</td>
<td>5.465 ± 0.066</td>
<td>-0.002 ± 0.008 (-0.018 to 0.015)</td>
<td>0.0 ± 0.2 (-0.3 to 0.3)</td>
<td>0.992 (0.984 to 0.996)</td>
</tr>
<tr>
<td>60 m (s)</td>
<td>6.441 ± 0.128</td>
<td>6.440 ± 0.125</td>
<td>-0.001 ± 0.010 (-0.019 to 0.018)</td>
<td>0.0 ± 0.2 (-0.3 to 0.3)</td>
<td>0.997 (0.996 to 0.998)</td>
</tr>
<tr>
<td>70 m (s)</td>
<td>7.186 ± 0.087</td>
<td>7.196 ± 0.089</td>
<td>0.005 ± 0.007 (-0.008 to 0.019)</td>
<td>0.1 ± 0.1 (-0.1 to 0.3)</td>
<td>0.995 (0.976 to 0.998)</td>
</tr>
<tr>
<td>80 m (s)</td>
<td>8.203 ± 0.171</td>
<td>8.204 ± 0.172</td>
<td>0.001 ± 0.006 (-0.011 to 0.013)</td>
<td>0.0 ± 0.1 (-0.1 to 0.2)</td>
<td>0.999 (0.999 to 0.999)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sprint Velocities</th>
<th>Measured</th>
<th>Modelled</th>
<th>Mean bias ± SD (95% LOA)</th>
<th>% Mean bias ± SD (95% LOA)</th>
<th>ICC (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20 m (m·s⁻¹)</td>
<td>7.10 ± 0.12</td>
<td>7.10 ± 0.12</td>
<td>-0.01 ± 0.02 (-0.05 to 0.03)</td>
<td>-0.1 ± 0.3 (-0.6 to 0.5)</td>
<td>0.985 (0.975 to 0.990)</td>
</tr>
<tr>
<td>20-40 m (m·s⁻¹)</td>
<td>10.83 ± 0.24</td>
<td>10.85 ± 0.25</td>
<td>0.03 ± 0.08 (-0.14 to 0.19)</td>
<td>0.2 ± 0.8 (-1.3 to 1.8)</td>
<td>0.935 (0.896 to 0.959)</td>
</tr>
<tr>
<td>40-60 m (m·s⁻¹)</td>
<td>11.28 ± 0.34</td>
<td>11.26 ± 0.30</td>
<td>-0.01 ± 0.08 (-0.17 to 0.15)</td>
<td>-0.1 ± 0.7 (-1.5 to 1.3)</td>
<td>0.967 (0.950 to 0.979)</td>
</tr>
<tr>
<td>60-80 m (m·s⁻¹)</td>
<td>11.36 ± 0.32</td>
<td>11.35 ± 0.33</td>
<td>-0.01 ± 0.10 (-0.20 to 0.18)</td>
<td>-0.1 ± 0.9 (-1.8 to 1.6)</td>
<td>0.955 (0.932 to 0.971)</td>
</tr>
<tr>
<td>Max Velocity (m·s⁻¹)</td>
<td>11.39 ± 0.33</td>
<td>11.37 ± 0.33</td>
<td>-0.02 ± 0.07 (-0.15 to 0.11)</td>
<td>-0.2 ± 0.6 (-1.3 to 1.0)</td>
<td>0.978 (0.966 to 0.986)</td>
</tr>
</tbody>
</table>

CI = Confidence interval; LOA = Limits of agreement
20, 40, 60 & 80 m splits (n = 82)
10, 30, 50 & 70 m splits (n = 33)
Descriptive statistics (mean ± SD), mean differences and effect sizes between faster and slower groups are provided in Table 3.4. The faster group had a significantly faster 100 m sprint performance time (extremely large effect), a shorter RT (moderate effect) and were faster over all sections of the 100 m (very large – extremely large effects). The faster group spent a significantly higher percentage of time, relative to the slower group, in the 0-20 m (large effect) and 20-40 m (moderate effect) sections whereas the slower group spent a significantly higher percentage of time in the 40-60 m (large effect), 60-80 m (small effect) and 80-100 m (moderate effect) sections. No significant difference was found for relative percentage of RT.

The faster group also had a significantly higher $v_{\text{max}}$ (very large effect) and significantly lower velocity, as a percentage of $v_{\text{max}}$, at 20 and 40 m (large effects) and a significantly lower average velocity, as a percentage of $v_{\text{max}}$, over the 0-20 (large effect) and 20-40 m sections (moderate effect). A significantly higher $\tau$ was found in the faster group (moderate effect) whereas a small effect was found for $v_{\text{Loss}}$ with the faster group displaying lower values however this was not significant ($p = 0.085$).
Table 3.4: Mean ± SD for all sprinters (n = 82), faster sprinters (n=28) and slower sprinters (n=28), mean difference with 95% CI and Cohen’s d
effect size for all sprint variables.

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th>Faster</th>
<th>Slower</th>
<th>Mean Difference (95% CI)</th>
<th>% Mean Difference (95% CI)</th>
<th>P Value</th>
<th>Cohen’s d (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 m Sprint Performance (s)</td>
<td>10.02 ± 0.23</td>
<td>9.77 ± 0.10</td>
<td>10.28 ± 0.09</td>
<td>-0.50 (-0.55 to -0.46)</td>
<td>-5.2 (-5.7 to -4.7)</td>
<td>&lt;0.001**</td>
<td>-5.13 (-5.63 to -4.62)</td>
</tr>
<tr>
<td>( v_{\text{max}} ) (m·s^{-1})</td>
<td>11.37 ± 0.33</td>
<td>11.71 ± 0.19</td>
<td>11.01 ± 0.14</td>
<td>0.70 (0.61 to 0.79)</td>
<td>6.0 (5.2 to 6.8)</td>
<td>&lt;0.001**</td>
<td>3.69 (3.21 to 4.17)</td>
</tr>
<tr>
<td>( \tau ) (s)</td>
<td>1.16 ± 0.068</td>
<td>1.182 ± 0.057</td>
<td>1.131 ± 0.060</td>
<td>0.050 (0.019 to 0.082)</td>
<td>4.3 (1.6 to 6.9)</td>
<td>0.002**</td>
<td>0.81 (0.31 to 1.31)</td>
</tr>
<tr>
<td>( v_{\text{loss}} ) (%)</td>
<td>3.30 ± 1.23</td>
<td>2.87 ± 1.30</td>
<td>3.37 ± 0.78</td>
<td>-0.51 (-1.08 to 0.07)</td>
<td>-17.6 (-37.7 to 2.5)</td>
<td>0.085</td>
<td>-0.44 (-0.94 to 0.06)</td>
</tr>
</tbody>
</table>

**Race Sections**

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th>Faster</th>
<th>Slower</th>
<th>Mean Difference (95% CI)</th>
<th>% Mean Difference (95% CI)</th>
<th>P Value</th>
<th>Cohen’s d (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT (s)</td>
<td>0.146 ± 0.018</td>
<td>0.136 ± 0.016</td>
<td>0.151 ± 0.017</td>
<td>-0.015 (-0.024 to -0.006)</td>
<td>-10.8 (-17.3 to -4.3)</td>
<td>0.002**</td>
<td>-0.83 (-1.34 to -0.33)</td>
</tr>
<tr>
<td>0-20 m (s)</td>
<td>2.82 ± 0.05</td>
<td>2.77 ± 0.02</td>
<td>2.86 ± 0.03</td>
<td>-0.08 (-0.10 to -0.07)</td>
<td>-3.0 (-3.5 to -2.5)</td>
<td>&lt;0.001**</td>
<td>-2.96 (-3.47 to -2.46)</td>
</tr>
<tr>
<td>20-40 m (s)</td>
<td>1.85 ± 0.04</td>
<td>1.81 ± 0.02</td>
<td>1.89 ± 0.02</td>
<td>-0.08 (-0.10 to -0.07)</td>
<td>-4.7 (-5.3 to -4.1)</td>
<td>&lt;0.001**</td>
<td>-4.02 (-4.52 to -3.52)</td>
</tr>
<tr>
<td>40-60 m (s)</td>
<td>1.78 ± 0.05</td>
<td>1.72 ± 0.03</td>
<td>1.83 ± 0.02</td>
<td>-0.11 (-0.13 to -0.10)</td>
<td>-6.7 (-7.5 to -5.9)</td>
<td>&lt;0.001**</td>
<td>-4.24 (-4.74 to -3.74)</td>
</tr>
<tr>
<td>60-80 m (s)</td>
<td>1.76 ± 0.05</td>
<td>1.72 ± 0.03</td>
<td>1.82 ± 0.03</td>
<td>-0.10 (-0.12 to -0.08)</td>
<td>-5.9 (-6.8 to -5.0)</td>
<td>&lt;0.001**</td>
<td>-3.20 (-3.71 to -2.70)</td>
</tr>
<tr>
<td>80-100 m (s)</td>
<td>1.82 ± 0.06</td>
<td>1.76 ± 0.03</td>
<td>1.88 ± 0.03</td>
<td>-0.12 (-0.14 to -0.10)</td>
<td>-6.9 (-7.9 to -5.8)</td>
<td>&lt;0.001**</td>
<td>-3.32 (-3.82 to -2.82)</td>
</tr>
</tbody>
</table>

**Relative Race Sections**

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th>Faster</th>
<th>Slower</th>
<th>Mean Difference (95% CI)</th>
<th>% Mean Difference (95% CI)</th>
<th>P Value</th>
<th>Cohen’s d (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT (%)</td>
<td>1.4 ± 0.2</td>
<td>1.4 ± 0.2</td>
<td>1.5 ± 0.2</td>
<td>-0.1 (-0.2 to 0.0)</td>
<td>-5.3 (-11.5 to 1.0)</td>
<td>0.097</td>
<td>-0.42 (-0.92 to 0.08)</td>
</tr>
<tr>
<td>0-20 m (%)</td>
<td>27.7 ± 0.4</td>
<td>28.0 ± 0.3</td>
<td>27.4 ± 0.4</td>
<td>0.6 (0.4 to 0.8)</td>
<td>2.1 (1.5 to 2.7)</td>
<td>&lt;0.001**</td>
<td>1.66 (1.16 to 2.17)</td>
</tr>
<tr>
<td>20-40 m (%)</td>
<td>18.2 ± 0.2</td>
<td>18.2 ± 0.1</td>
<td>18.1 ± 0.2</td>
<td>0.1 (0.02 to 0.2)</td>
<td>0.5 (0.1 to 1.0)</td>
<td>0.018*</td>
<td>0.61 (0.11 to 1.11)</td>
</tr>
<tr>
<td>40-60 m (%)</td>
<td>17.5 ± 0.2</td>
<td>17.4 ± 0.2</td>
<td>17.6 ± 0.1</td>
<td>-0.2 (-0.3 to -0.2)</td>
<td>-1.4 (-1.8 to -0.9)</td>
<td>&lt;0.001**</td>
<td>-1.52 (-2.03 to -1.02)</td>
</tr>
<tr>
<td>60-80 (%)</td>
<td>17.3 ± 0.2</td>
<td>17.3 ± 0.2</td>
<td>17.4 ± 0.2</td>
<td>-0.1 (-0.2 to -0.0)</td>
<td>-0.6 (-1.2 to -0.1)</td>
<td>0.034*</td>
<td>-0.54 (-1.04 to -0.04)</td>
</tr>
<tr>
<td>80-100 (%)</td>
<td>17.9 ± 0.3</td>
<td>17.8 ± 0.2</td>
<td>18.0 ± 0.2</td>
<td>-0.3 (-0.4 to -0.2)</td>
<td>-1.5 (-2.2 to -0.9)</td>
<td>&lt;0.001**</td>
<td>-1.12 (-1.63 to -0.62)</td>
</tr>
</tbody>
</table>

**Velocity**

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th>Faster</th>
<th>Slower</th>
<th>Mean Difference (95% CI)</th>
<th>% Mean Difference (95% CI)</th>
<th>P Value</th>
<th>Cohen’s d (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Velocity 0-20 m (%( v_{\text{max}} ))</td>
<td>62.4 ± 1.5</td>
<td>61.6 ± 1.1</td>
<td>63.6 ± 1.3</td>
<td>-2.0 (-2.6 to -1.3)</td>
<td>-3.2 (-4.3 to -2.1)</td>
<td>&lt;0.001**</td>
<td>-1.52 (-2.02 to -1.02)</td>
</tr>
<tr>
<td>Average Velocity 20-40 m (%( v_{\text{max}} ))</td>
<td>95.1 ± 1.5</td>
<td>94.6 ± 1.2</td>
<td>96.0 ± 1.5</td>
<td>-1.5 (-2.2 to -0.9)</td>
<td>-1.6 (-2.3 to -0.8)</td>
<td>&lt;0.001**</td>
<td>-1.01 (-1.52 to -0.51)</td>
</tr>
<tr>
<td>20 m Velocity (%( v_{\text{max}} ))</td>
<td>91.1 ± 1.2</td>
<td>90.5 ± 1.0</td>
<td>92.0 ± 0.9</td>
<td>-1.5 (-2.0 to -1.0)</td>
<td>-1.7 (-2.3 to -1.2)</td>
<td>&lt;0.001**</td>
<td>-1.56 (-2.06 to -1.06)</td>
</tr>
<tr>
<td>40 m Velocity (%( v_{\text{max}} ))</td>
<td>98.2 ± 0.5</td>
<td>97.9 ± 0.4</td>
<td>98.5 ± 0.3</td>
<td>-0.6 (-0.8 to -0.4)</td>
<td>-0.6 (-0.8 to -0.4)</td>
<td>&lt;0.001**</td>
<td>-1.52 (-2.03 to -1.02)</td>
</tr>
</tbody>
</table>

CI = Confidence interval

**p ≤ 0.01; *p ≤ 0.05.**
The relationships between \( v_{\text{max}} \), 0-20, 20-40, 40-60, 60-80 and 80-100 m sprint times are shown in Table 3.5. All 20 m split times had a significant, near perfect negative correlation with \( v_{\text{max}} \) except for the 0-20 m split time which had a significant large negative correlation with \( v_{\text{max}} \).

Table 3.5: Correlation matrix between \( v_{\text{max}} \) and 20 m split times.

<table>
<thead>
<tr>
<th>( v_{\text{max}} ) (m \cdot s(^{-1}))</th>
<th>0-20 m (s)</th>
<th>20-40 m (s)</th>
<th>40-60 m (s)</th>
<th>60-80 m (s)</th>
<th>80-100 m (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.57**</td>
<td>-0.90**</td>
<td>-0.98**</td>
<td>-0.96**</td>
<td>-0.93**</td>
<td></td>
</tr>
<tr>
<td>(-0.73 to -0.40)</td>
<td>(-0.93 to -0.86)</td>
<td>(-0.99 to -0.96)</td>
<td>(-0.97 to -0.93)</td>
<td>(-0.95 to -0.89)</td>
<td></td>
</tr>
</tbody>
</table>

Note: Results are presented as \( r \) (95% CI) with statistically significant correlations presented in bold.

**Correlation is significant (\( P < 0.001 \)).

Scatterplots illustrating the relationship between \( \tau \), 20 and 40 m velocity and average velocity over 0-20 and 20-40 m sections are given in Figure 3.1. Significant near perfect negative correlations were found between \( \tau \), velocity at 20 and 40 m and average velocity over 0-20 whereas a significant large negative correlation was found between \( \tau \) and average velocity over 20-40 m.
Scatter plots illustrating the relationship between 100 m sprint performance, $v_{\text{max}}$, $\tau$ and $v_{\text{Loss}}$ along with the relationships between $v_{\text{max}}$, $\tau$ and $v_{\text{Loss}}$ are given in Figure 3.2. Significant negative correlations were found between 100 m sprint performance and $v_{\text{max}}$ (near perfect) and $\tau$ (moderate). No significant relationship was found between 100 m sprint performance and $v_{\text{Loss}}$. A significant positive correlation was found between $v_{\text{max}}$ and $\tau$ (large) whereas no significant relationship was found between $v_{\text{max}}$ and $v_{\text{Loss}}$. After controlling for $v_{\text{max}}$, a significant, very large positive correlation was found between 100 m sprint performance and $\tau$ ($r = 0.86$, 95% CI: 0.78 to 0.91, $p < 0.001$) whereas the correlation between 100 m sprint performance and $v_{\text{Loss}}$ was not significant ($r = 0.14$, 95% CI: -0.10 to 0.37, $p = 0.220$).
Figure 3.2: Scatter plots illustrating the associations between 100 m sprint performance, $v_{\text{max}}$, $\tau$ and $v_{\text{Loss}}$ (a – c) and the associations between $v_{\text{max}}$, $\tau$ and $v_{\text{Loss}}$ (d – e). **Correlation significant ($p < 0.01$).
3.4 Discussion
The results in Table 3.3 suggest that the four split time modelling method provided an accurate estimation of sprint times for every 10 m section from 20 m to 80 m, average velocities for each 20 m section (0-20, 20-40, 40-60 and 60-80 m) and \( v_{\text{max}} \). The curves generated by the modelling method were derived from two input parameters, \( v_{\text{hmax}} \) and \( \tau \). Only \( v_{\text{hmax}} \) could be compared to directly measured data i.e. \( v_{\text{max}} \). To indirectly assess the accuracy of \( \tau \), sprint times and velocities that were not directly used to generate the distance-time and velocity-time curves were assessed. This approach was successful in demonstrating the accuracy of the four split time method except for the estimation of 10 m time. This suggests some uncertainty about the accuracy of velocity estimates over the first 10 m, however this could not be directly assessed in the current study.

The current study used only elite male data; thus the four split time method may not be as accurate for female sprinters or sprinters of a lower performance level. The mono-exponential function can only model the acceleration phase of a sprint; therefore, the accuracy may be affected due to differences in acceleration ability e.g. time to reach \( v_{\text{max}} \) with elite male sprinters accelerating over a longer distance and for a longer time compared to their female and less skilled counterparts (Volkov and Lapin 1979; Letzelter 2006; Mackala 2007; Maćkała et al. 2015; Slawinski et al. 2017). Future research on female athletes is therefore warranted as other split combinations e.g. 10, 20, 40 and 60 m may be more appropriate. Additionally, it is recommended that coaches or researchers using the four split time modelling method on 100 m sprint data should assess the input (\( v_{\text{max}} \)) and output data to confirm the accuracy of the method.

Faster sprinters had a significantly higher \( v_{\text{max}} \) (6%) and a higher \( \tau \) (4.3%) than slower sprinters. The difference in \( v_{\text{max}} \) was considered very large (ES = 3.69) whereas the difference in \( \tau \) was considered moderate (ES = 0.81). This demonstrates that \( v_{\text{max}} \) is the most important variable for elite 100 m sprinters. The moderate difference in \( \tau \) can likely be explained by the very large difference between groups in \( v_{\text{max}} \). As \( \tau \) represents the ratio of maximal horizontal velocity to the maximal horizontal acceleration, a higher \( v_{\text{max}} \), without a proportional increase in maximal horizontal acceleration, would result in a higher ratio and thus a higher \( \tau \). This finding is contrary to Clark et al. (2017) who found no significant difference in \( \tau \) between...
NFL Combine athletes with a higher $v_{\text{max}}$ and athletes with a lower $v_{\text{max}}$, even with very large differences in $v_{\text{max}}$. Maximal horizontal acceleration can be assessed by dividing $v_{\text{max}}$ by $\tau$. Utilising the mean data reported in Clark et al. (2017), maximal acceleration values of 12.49 m.s$^{-2}$ and 11.07 m.s$^{-2}$ were estimated for the faster and slower groups respectively representing a 1.41 m.s$^{-2}$ (11.3%) mean difference. In contrast, maximal acceleration values of $9.92 \pm 0.35$ m.s$^{-2}$ and $9.75 \pm 0.43$ m.s$^{-2}$ were found for faster and slower sprinters in the current study respectively. This represents a mean difference of 0.17 m.s$^{-2}$ (1.7%) and was not significant ($p = 0.105$).

A significant moderate difference was found for RT with faster sprinters reacting 10.8% quicker than slower sprinters. This is supported by previous research which found a significant, weak positive correlation ($r = 0.292$) between RT and 100 m sprint time in 674 male sprinters during IAAF athletic world championships (Tønnessen et al. 2013). The faster sprinters were quicker over all 20 m sections, however the mean differences were larger in the 40-60, 60-80 and 80-100 m sections (-6.6, -5.9 and -6.9% respectively) relative to the 0-20 and 20-40 m sections (-3.0 and -4.7% respectively). This explains why the faster sprinters spent a significantly higher percentage of time in the 0-20 and 20-40 m sections and a lower percentage of time in the 40-60, 60-80 and 80-100 m sections compared to the slower sprinters. These differences in absolute and relative times are not surprising since the faster and slower groups were initially created based on 100 m sprint performance times.

The faster group had a 17.6% lower mean $v_{\text{Loss}}$ than the slower group although this difference was not statistically significant. This suggests that although the faster group had a higher velocity in the final 20 m, as demonstrated by the faster 80-100 m times, faster sprinters were not better able to maintain their maximum speed during the final phase of the race in relative terms. It is worth noting that larger variance was recorded in the faster group (SD: $\pm 1.3\%$; Range: 0.6 to 5.6%) compared to the slower group (SD: $\pm 0.78\%$; range: 1.6 to 5.2%). Slawinski et al. (2017) found that world class male sprinters had a significantly lower loss in relative velocity compared to world class female sprinters. A potential explanation provided by the authors was that the women in that study reached $v_{\text{max}}$ earlier and thus had a deceleration phase which was 1.77 s longer than the men which would lead to greater relative fatigue effects in women (Slawinski et al. 2017). Additional research is therefore warranted.
to determine whether this is the case for male sprinters over a wider range of performance levels.

Faster sprinters reached significantly lower velocities relative to $v_{\text{max}}$, at 20, 40 m and on average over the 0-20 and 20-40 m sections. This is consistent with the difference found for $\tau$ since higher $\tau$ values indicate the ability to quickly reach a high percentage of $v_{\text{max}}$. This is well supported by the literature as better sprinters accelerate for longer and so will not achieve the same relative velocities as their slower counterparts (Volkov and Lapin 1979; Letzelter 2006; Clark et al. 2017) reported relative velocities of 97.2 ± 0.9% at 18.3 m in male NFL Combine athletes which is considerably higher than the relative velocities reported here at 20 m (91.1 ± 1.2%). The athletes in the current study achieved higher $v_{\text{max}}$ values (11.37 ± 0.33 m·s$^{-1}$ versus 9.08 ± 0.62 m·s$^{-1}$) compared to the athletes in Clark et al. (2017). Therefore, caution is advised when comparing $\tau$ values between studies on different athletic populations. Differences in method-related factors such as the sprint distance studied (e.g. 36.6 m versus 80 m), will affect $\tau$, as shorter distances may not be sufficient for some athletes to reach their true $v_{\text{max}}$. This will result in the underestimation of that athlete’s $\tau$. Additionally, the start type i.e. block start, standing start, three point start will result in different values for initial acceleration which will subsequently affect $\tau$.

The results in Table 3.5 highlight the critical importance of $v_{\text{max}}$ to each 20 m section of the 100 m sprint with higher $v_{\text{max}}$ values associated with quicker sprint times. While stronger absolute correlations were found for the 20-40, 40-60, 60-80 and 80-100 m sections ($r \leq -0.90$), a strong negative correlation was still found for the 0-20 m section ($r = -0.57$). This suggests that $v_{\text{max}}$ plays an important role in the initial acceleration phase, which is consistent with research on lower level male sprinters (mean ± SD 100 m PB: 11.17 ± 0.33 s) and athletes from field sports (Volkov and Lapin 1979; Clark et al. 2017). In the current study, the mean average 0-20 m velocity as a percentage of $v_{\text{max}}$ was 62.4%. A higher $v_{\text{max}}$ will thus lead to a higher average 0-20 m velocity in absolute units and thus quicker 20 m sprint times compared to an athlete with a lower $v_{\text{max}}$.

The significant correlations presented in Figure 3.1 indicate that as $\tau$ values increase the percentage of $v_{\text{max}}$ achieved decreases. These findings provide further support for the use of $\tau$ as an indicator of an athlete’s relative acceleration ability. The relationship between $\tau$ and...
average velocity was lower for the 20-40 m section compared to the 0-20 m section ($\tau = -0.68$ versus -0.93 respectively), which suggests that $\tau$ is a better indicator of relative acceleration ability over the initial 20 m, however the relationship is still large in the 20-40 m section.

Decreasing $v_{\text{max}}$ with no change in initial acceleration will lead to a decrease in $\tau$ and thus a greater relative acceleration ability; however, this change is entirely counterproductive and will lead to slower sprint times overall. Increasing maximal acceleration with no change in $v_{\text{max}}$ will lead to a decreased $\tau$ and thus improve an athlete’s relative acceleration ability. This will subsequently enhance overall 100 m sprint performance as an athlete will reach higher levels of their $v_{\text{max}}$ earlier. Sprint, technical or strength training methods that develop maximal acceleration or that can improve the technical ability to apply force and thereby maintain a higher level of acceleration as a sprint progresses are needed. Promising research using heavy sled training has demonstrated improvements in maximal horizontal force which logically suggests improvements in maximal horizontal acceleration in male amateur soccer players (Morin et al. 2017); however, such findings in an elite sprinter population have yet to be reported.

The results presented in Figure 3.2 are consistent with other research and indicate a significant negative correlation between 100 m sprint performance time and $v_{\text{max}}$ (Volkov and Lapin 1979; Ryu et al. 2012; Slawinski et al. 2017). This can be explained by several factors that have already been discussed. Briefly, sprinters with a higher $v_{\text{max}}$ will reach higher velocities during the initial acceleration phase and will take longer to reach $v_{\text{max}}$. Subsequently, a longer acceleration and maximum velocity phase results in a shorter deceleration phase and thus the decrease in sprint velocity as a result of fatigue is limited (Volkov and Lapin 1979; Slawinski et al. 2017).

This is the first study to assess the relationship between 100 m sprint performance, $\tau$ and $v_{\text{Loss}}$ in elite male sprinters. A moderate negative correlation was found for $\tau$ which indicates that higher $\tau$ values were related to quicker sprint performance times. This is consistent with the findings of Volkov and Lapin (1979) who found a large negative correlation ($r= -0.52$) between 100 m time and $\tau$. In that paper, $\tau$ was derived using a bi-exponential function which included the deceleration phase of a 100 m sprint in the model prediction. This negative relationship between $\tau$ and performance is counterintuitive since athletes with greater relative
acceleration ability would be expected to be quicker over 100 m. However, this can be explained by the significant large positive correlation found between $v_{\text{max}}$ and $\tau$ in the current study. As higher $\tau$ values were associated with higher $v_{\text{max}}$ values and higher $v_{\text{max}}$ values were associated with quicker 100 m sprint performance times, $v_{\text{max}}$ was therefore a confounding variable. By controlling for $v_{\text{max}}$, a significant very large positive correlation was found between $\tau$ and 100 m sprint performance which suggests that for athletes with similar $v_{\text{max}}$ values, lower $\tau$ values were associated with quicker 100 m sprint performances which is consistent with the conceptual understanding of $\tau$.

No significant relationship was found between $v_{\text{max}}$ and $v_{\text{Loss}}$ ($r = -0.18$, $p = 0.102$) and between 100 m sprint performance and $v_{\text{Loss}}$ even when controlling for $v_{\text{max}}$ ($r = 0.14$, $p = 0.220$). The lack of a significant correlation between $v_{\text{max}}$ and $v_{\text{Loss}}$ suggests that the ability to maintain maximal velocity is independent of an athlete’s maximum speed capabilities. This ability, therefore, requires specific attention in training, however future research is required to confirm this finding and to assess if this is consistent in sprinters and team sport players of varying levels of ability.

The 100 m sprint is a multi-dimensional skill and as the science underpinning the training and coaching of 100 m sprinters continues to improve, it is likely that success at major championships will require sprinters to excel at all factors assessed in the current study. This includes a short RT, a high relative acceleration ability, a high $v_{\text{max}}$ and a low $v_{\text{Loss}}$. Each individual athlete will likely have strengths and weaknesses in each of these variables and these will manifest in terms of technical and physical deficiencies which should be examined in much more depth than the current study. These weaknesses should be highlighted by sprint coaches and support staff and progressively targeted during an athlete’s long term development. Future research should continue to assess the effectiveness of interventions to improve key race variables in both male and female sprinters over a wide range of performance levels.

There were several limitations with the current study that must be acknowledged. Firstly, wind speed was not factored into the current analysis. Although the wind speed was available for all performances (Range: -0.8 to 1.2 m·s$^{-1}$), performances were not corrected as each 20 m section would need to be adjusted in order to complete the current analysis. This would
require additional information e.g. projected frontal area and coefficient of drag which were not available. Secondly, since a field based technique (i.e. the four split time modelling method) was used to derive some of the key variables used in this study (e.g. τ, velocity at 20 and 40 m), the accuracy of this method is dependent on the quality of the input data. Furthermore, the measurement method was not consistent across all data sources with a wide range of instruments used which is understandable given the nature of the data set i.e. seven major events taking place between 1988 and 2017. The data were all collected by experienced biomechanical teams and researchers so it is likely that such measurement errors are minimal and thus would not have any considerable effect on the results of the present study.

3.5 Conclusion
A four split time approach can accurately model velocity-time and velocity-distance curves in elite male sprinters with 100 m sprint times ranging from 9.58 s to 10.59 s. Faster sprinters displayed higher $v_{\text{max}}$ and τ values than their slower counterparts. Faster sprinters also achieved a lower percentage of their $v_{\text{max}}$ over the 0-20 m and 20-40 m sections and at the 20 m and 40 m mark. No difference was found between groups in $v_{\text{Loss}}$. Maximum velocity had a strong negative correlation with the 0-20 m time and a near perfect negative correlation with all other 20 m sections and overall 100 m sprint performance time which further demonstrates the importance of $v_{\text{max}}$ to a 100 m sprinter. The variable τ is a very useful indicator of a sprinter’s relative acceleration ability with a lower τ associated with the ability to achieve a high percentage of $v_{\text{max}}$, especially over the first 20 m. Furthermore, a lower τ is associated with a quicker 100 m sprint performance after controlling for $v_{\text{max}}$. Coaches and researchers are encouraged to utilise the approach adopted in the current study to assess several key race variables that describe an athlete’s performance capacities which can be subsequently used to further inform training. This chapter highlights that although both acceleration and speed endurance are important to a 100 m sprint, maximum velocity is the strongest correlate to 100 m sprint time. Consequently, Chapter 5 will attempt to assess the influence of maximum strength and reactive strength to maximum velocity and other sprint performance indicators in male and female sprinters.
Chapter 4: Influence of Reactive and Maximum Strength Indicators on Sprint Performance

This chapter has been published in the following journal:

4.1 Introduction

Sprint performance is critical to success in various team and individual sports. The findings of Chapter 3 suggest that the ability to rapidly accelerate and especially the ability to reach a high maximum velocity are crucial to 100 m sprint performance (Mackala 2007; Slawinski et al. 2017; Chapter 3). The 100 m sprint can be broken down simply, into three main phases: the acceleration phase, the maximum velocity phase and the deceleration phase (Delecluse et al. 1995). Furthermore, each phase can be sub-divided in various ways e.g. the initial acceleration phase (0-20 m) and the pick up phase (20-40 m) (Maćkała et al. 2015). Consequently, sprinting can be considered a multidimensional skill with different kinematic and kinetic requirements during the distinct phases (Delecluse et al. 1995). Accordingly, different strength capabilities play relatively larger roles throughout the performance of a sprint (Nagahara et al. 2014).

A novel field method of profiling athletes’ horizontal force-velocity relationship over 40 m has recently been developed (Samozino et al. 2016). Mechanical variables such as the theoretical maximum horizontal component of ground reaction force ($F_0$), theoretical maximum horizontal velocity ($v_0$) and the maximum horizontal mechanical power ($P_{\text{max}}$) produced can all be measured during accelerative performance (Samozino et al. 2016). Research on sprint athletes has found that maximum velocity and mean 100 m velocity were both very strongly correlated with $P_{\text{max}}$ (Morin et al. 2012). In contrast, Slawinski et al. (2017) found no correlation between $P_{\text{max}}$ and 100 m time, whereas $v_0$ had a very large negative correlation with $P_{\text{max}}$ in world class athletes. It is suggested that $P_{\text{max}}$ may be more likely related to performance over shorter distances i.e. 40 or 60 m where fatigue is limited (Slawinski et al. 2017). This is supported by Rabita et al. (2015) who found that maximal velocity achieved over 40 m and 40 m performance in elite and sub elite sprinters had an almost perfect positive and very large positive correlation with $P_{\text{max}}$ and $v_0$ respectively.

The ground contact phase of sprinting involves the coupling of an eccentric contraction with a concentric contraction. This is termed the stretch shortening cycle (SSC) and it is frequently used in many additional sports movements; e.g. in the leg extensor muscles during jumping and hopping (Nicol et al. 2006). The SSC has been classified as either fast, where contact times (CTs) < 0.250 s, or slow, where CTs > 0.250 s (Schmidtbleicher 1992). Therefore, sprinting is considered a fast SSC activity as a sprinter’s CT after the initial block push off, is below 0.250 s for each step with CTs progressively decreasing throughout the acceleration
phase with values as low as ~0.090-0.120 s reported at maximum velocity (Kuitunen et al. 2002; Debaere et al. 2013b). Traditionally, fast SSC performance has been assessed through the measurement of the reactive strength index (RSI) which is usually calculated by dividing the jump height by the contact time in a specific jump (Young 1995). The RSI has been assessed during drop jumps, rebound jumps and ankle jumps (hopping) (Young et al. 1995; Harper 2011; Nagahara et al. 2014).

The association between RSI and sprint performance in sprint athletes has been previously studied with contrasting results. Young et al. (1995) found no relationship between 2.5 m and 50 m sprint times and drop jump RSI in male and female sprinters. In contrast, Hennessy and Kilty (2001) found very large negative correlations between sprint times over 30 m and 100 m and RSI in female sprinters. Furthermore, Smirniotou et al. (2008) found moderate to large negative correlations between sprint performances over 10, 30, 60 and 100 m and drop jump RSI in male sprinters. Nagahara et al. (2014) assessed RSI during rebound jumps (termed the “rebound jump index”) and bilateral vertical hops (termed the “ankle jump index”) along with sprint time and individual step acceleration over 60 m. Although rebound jump RSI was not related to any of the sprint measures, hop RSI had a moderate negative relationship with 60 m time and a moderate to large positive relationship with step acceleration over the 23 – 34 m interval. Additionally, Nagahara et al. (2014) found no relationship between rebound jump RSI and hop RSI. The relationship between hop RSI and drop jump RSI has yet to be assessed. This warrants investigation as hop RSI may provide coaches with an additional insight into the reactive strength capabilities of their athletes.

Sprinting requires the production of very large forces over very short time periods. Consequently, sprint coaches utilize a variety of training modalities to develop different strength qualities; these may include reactive strength and maximum strength training performed throughout the training cycle (Bolger et al. 2016). Maximum strength has been defined as the ability to voluntarily generate maximal force under specified conditions (Sale 1991). Strength tests such as the back squat and isometric squat have previously been used with sprint athletes with very strong negative correlations found between relative 1RM and 100 m time (Meckel et al. 1995) and between peak force (PF) and maximum velocity (Young et al. 1995). The isometric mid-thigh pull (IMTP) has become a popular method of assessing maximum strength as the peak force applied during the pull can be measured directly from a force platform. Several authors have assessed peak force and relative peak force measured in
an IMTP with sprint performance in team sport athletes with contrasting results. Significant relationships have been found between PF and 5 and 20 m times (Thomas et al. 2015) and between relative PF and 10 m time (West et al. 2011; Wang et al. 2016). Wang et al. (2016) however, found no relationship between PF and short sprint performance (5 m and 10 m). It is not currently known whether stronger sprint athletes, as measured by the IMTP, reach higher maximum velocities, produce higher levels of maximal mechanical power or apply greater maximal theoretical horizontal forces during a sprint.

The primary aim of the current study was to assess the relationship between maximal strength, reactive strength, as measured in vertical hopping and drop jumping, and sprint performance. A secondary aim was to evaluate the differences between male and female sprinters’ maximal strength, reactive strength and sprint performance.

4.2 Methods
4.2.1 Experimental Approach to the Problem
A cross sectional research design was undertaken over two days of testing. On day one subjects performed 40 m sprints on an indoor athletic track. Sprint mechanical properties $F_0$, $v_0$, $P_{\text{max}}$ and max velocity were calculated in addition to split times from 0-10 m, 10-20 m, 20-30 m and 30-40 m and 40 m sprint time. On the second day of testing peak force and relative peak force values were measured during isometric mid-thigh pulls and CT, JH and RSI measures were calculated during drop jumps and vertical hopping tests. All testing on day two was performed in a biomechanical laboratory. Test days were separated by no longer than seven days.

4.2.2 Subjects
Twenty eight sprinters consisting of fourteen men (mean ± SD, age: 22 ± 2 years; body height: 1.82 ± 0.07 m; body mass: 73.1 ± 6.8 kg) and fourteen women (mean ± SD, age: 22 ± 4 years; body height: 1.72 ± 0.07 m; body mass: 64.4 ± 4.6 kg) agreed to participate in this investigation. Fifteen of the athletes competed regularly at an international level (seven men and eight women) while the remaining thirteen athletes competed regularly at a national level (seven men and six women). All athletes had at least two years of sprint and plyometric training experience. The athletes’ regular weekly conditioning programme consisted of 3 – 4 sprint training sessions which included a mixture of technical, acceleration, maximum speed and speed endurance sessions. Athletes typically performed two conditioning sessions a week.
distinct from sprinting sessions which included a mixture of hurdle jump, medicine ball, bounding and hopping exercises in addition to conventional strength training exercises and variations e.g. Romanian deadlifts. Ethical approval was provided by the Institution’s Research Ethics Committee. Additionally, athletes were informed of the benefits and risks of the investigation and written consent forms were completed prior to testing in compliance with the Declaration of Helsinki.

4.2.3 40 m Sprint Testing

Following an individualized, race specific warm up, lasting ~30 minutes, athletes completed three maximal effort 40 m sprints from a block start with the first trial acting as a familiarization trial. Six minutes of recovery time were provided with additional time granted if requested. To ensure athletes continued sprinting at maximal effort for the entire 40 m, coloured cones were placed at 45 m and athletes were instructed not to begin their deceleration until they had passed the cones. Racetime 2, dual-beam timing gates (Microgate, Bolzano, Italy) were positioned at 10 m, 15 m, 20 m, 30 m and 40 m. Split times from 0-10 m, 10-20 m, 30-40 m, and overall 40 m were recorded in addition to maximal velocity which was calculated as the fastest 10 m split time divided by the distance i.e. 10 m. Timing was initiated at the instant the athlete’s hand left the track surface using a previously validated protocol which synchronised timing gates to the Optojump™ system which is an optical measuring unit (Healy et al. 2016). This protocol enabled the measurement of the true 10 m movement time.

In addition to sprint performance measures, sprint mechanical properties were calculated based on the five timing gate split times using the methods of Samozino et al. (2016). The horizontal velocity of the center of mass ($v_h$) versus time ($t$) curve was modelled using the same mono-exponential function used in Chapter 3 (Samozino et al. 2016):

$$v_h(t) = v_{h\text{max}} \cdot (1 - e^{-\frac{t}{\tau}}) \quad \text{Eq. 1.}$$
where, \( v_{h\text{max}} \) is the maximal velocity, \( t \) is the time and \( \tau \) is the acceleration time constant which represents the ratio of maximal velocity to maximal acceleration. By integrating equation 1, an equation for the horizontal position of the center of mass can be derived:

\[
x_h(t) = v_{h\text{max}} \cdot \left( t + \tau \cdot e^{-\frac{t}{\tau}} \right) - v_{h\text{max}} \cdot \tau \quad \text{Eq. 2.}
\]

Using equation 2 and the Microsoft Excel Solver function, the best approximations of \( v_{h\text{max}} \) and \( \tau \) were calculated using a least squares approach between the raw position time data, collected from the timing gates, and the modelled position time data. The approximated \( v_{h\text{max}} \) had a near perfect correlation with the maximum velocity recorded during the sprints \( (r = 0.992, \text{ICC} = 0.99) \). Once \( v_{h\text{max}} \) and \( \tau \) values were approximated, horizontal velocity time curves could be derived using equation 1. Velocity time curves were subsequently differentiated once with respect to time to give acceleration time curves \( a_h(t) \).

\[
a_h(t) = \left( \frac{v_{h\text{max}}}{\tau} \right) \cdot e^{-\frac{t}{\tau}} \quad \text{Eq. 3.}
\]

The net horizontal component of ground reaction force (GRF) applied to the center of mass was modelled over time as follows:

\[
F_h(t) = m \cdot a_h(t) + F_{aero}(t) \quad \text{Eq. 4.}
\]

Where \( m \) is the body mass of the sprinter and \( F_{aero}(t) \) is the estimated aerodynamic drag force the sprinter experienced throughout the sprint (van Ingen Schenau et al. 1991; Arsac and Locatelli 2002; Samozino et al. 2016). The maximal theoretical horizontal velocity \( (v_0) \) and maximal theoretical horizontal force \( (F_0) \) were calculated as the x and y intercept of the individual force-velocity relationships, determined via least squares regression, respectively (Samozino et al. 2016; Morin and Samozino 2016). The \( F_0 \) represents the maximal theoretical horizontal force applied by the athlete at the initial push i.e. when velocity is zero. The \( v_0 \) represents the maximal theoretical horizontal velocity of the athlete if net internal and external mechanical resistances, such as drag, were null (Samozino et al. 2016; Morin and Samozino 2016). The maximum mechanical power developed in the horizontal direction
\( P_{\text{max}} \) was calculated using the following equation validated by previous work (Samozino et al. 2012, Samozino et al. 2014):

\[
P_{\text{max}} = \frac{F_0 \cdot v_0}{4} \quad \text{Eq. 5.}
\]

Both \( F_0 \) and \( P_{\text{max}} \) were expressed relative to body mass.

4.2.4 Isometric Mid-Thigh Pull

A specific IMTP warm up, consisting of pulling the IMTP bar at an intensity of 50\%, 70\% and 90\% for a period of five seconds, was performed by each athlete (Beattie et al. 2016). The height of the IMTP bar was set individually so that each athlete could adopt the second pull position of the clean with an upright trunk and knee angle \( \sim 130\text{-}140^\circ \) (Stone et al. 2004; Haff et al. 2005). Following the warm up, athletes performed two maximal effort pulls separated by 3 minutes of rest. Athletes were instructed to adopt the second pull position and on the experimenter’s verbal command of “GO!” to pull as hard and as fast as possible for the full five seconds (Haff et al. 2005). IMTP testing was conducted with a custom-made isometric rack (Odin, Ireland) that enabled the placement of a steel bar at intervals of 50 mm. The rack was anchored to the laboratory floor and placed over two AMTI force platforms (Advanced Mechanical Technologies, MA, USA) operating at 1,000 Hz. PF was calculated directly from the force-time curve as the maximum force produced during each five second trial. Relative PF was also calculated by dividing PF by the athlete’s mass.

4.2.5 Drop Jumps

Following a standardised dynamic warm up, athletes performed three maximal effort drop jumps with the first jump serving as a practice trial and the two subsequent jumps retained for analysis. Athletes were instructed to keep their hands on their hips throughout the entire movement, to step directly off of the box i.e. avoid stepping down from the box or jumping off of the box, avoid any tucking motion in the air and to attempt to land in the same position as take-off. Additionally, athletes were instructed to aim to minimise CT while also trying to maximise JH during each jump (Young et al. 1995). All drop jumps were visually assessed by the experimenter and trials were repeated if any of the instructions were not correctly followed or if CT > 0.250 s. Thirty seconds of rest were provided between trials to avoid any
deleterious effects of fatigue on performance. Drop jumps were performed from a box height of 0.3 m with athletes landing on a force platform operating at 1,000 Hz.

The dependent variables calculated were: CT, JH and RSI. CTs were obtained directly from the force-time trace using a threshold of >10 N to determine contact and <10 N to determine flight. Flight time i.e. the time elapsed between the initiation of the flight phase and the subsequent contact phase was used to estimate JH using an adapted version of the second mathematical equation of linear motion i.e. \( JH = FT^2 \times 1.22625 \). RSI was calculated as JH divided by CT (Young 1995). The trial with the highest RSI was considered the best trial and was used for the final analysis.

4.2.6 Hopping Test
For the hopping test, participants performed two trials of a 10 s hopping test at a frequency of 2.2 Hz. A 2.2 Hz hopping frequency was chosen as this frequency elicits shorter CTs and greater ankle stiffness compared to unconstrained hopping and hopping at lower frequencies e.g. 1.5 Hz (Hobara et al. 2011; Mrdakovic et al. 2014). The hopping frequency was imposed via a metronome operating at 132 beats per minute. Participants were instructed: to land on the audible tone of the metronome, in the same position as take-off, to keep their hands on their hips throughout and to keep their legs as straight as possible by trying to avoid knee and hip flexion as much as possible (Nagahara et al. 2014). All trials were visually assessed by the same investigator to ensure consistent technique and remove invalid trials (i.e. where participants did not land on the force platform or took their hands off their hips). Similar to previous investigations, only hops that were performed within 2% (2.16 – 2.24 Hz) of the desired hopping frequency were included in the analysis (Farley and Morgenroth 1999). Similar to the ten to five repeated jump test, the five best hops, as determined by the highest RSIs, in each trial were used to calculate average values for CT, JH and RSI (Harper 2011). Dependent variables were calculated using the same methods described for the drop jumps.

4.2.7 Statistical Analyses
All variables were found to be normally distributed as the Shapiro-Wilk’s test had an alpha level > 0.05. Descriptive statistics for all variables were presented as mean ± SD. The test-retest reliability of each variable was assessed by calculating the single measure intraclass
correlation coefficient (ICC) with 95% CI and the typical error, expressed as a coefficient of variation (CV%) (Hopkins 2000).

Differences between men and women were assessed using independent samples t-tests and Cohen’s d effect size (ES) was used to assess the magnitude of differences between groups. The absolute value of the effect sizes were interpreted as trivial (ES < 0.2), small (0.2 ≤ ES < 0.6), moderate (0.6 ≤ ES < 1.2), large (1.2 ≤ ES < 2) very large (2 ≤ ES < 4) and extremely large (> 4) according to the scale proposed by Hopkins et al. (Hopkins et al. 2009).

Relationships between sprint, reactive strength and maximal strength measures were determined using Pearson’s product moment correlation with the alpha level set at 0.05. The strength of the correlations was evaluated as: trivial (0 – 0.09), small (0.1 – 0.29), moderate (0.3 – 0.49), large (0.5 – 0.69), very large (0.7 – 0.89), near perfect (0.9 – 0.99) and perfect (1) (Hopkins et al. 2009). Non-significant correlations were not interpreted. All statistical analyses apart from the CV% were performed using SPSS software (version 21.0, SPSS, Inc., IL, USA).

4.3 Results
The results of the reliability analysis for sprint, IMTP, DJ and Hop measures are presented in Table 1. All measures displayed excellent reliability with ICCs above 0.90 (Range: 0.93 – 0.99) and CV% below <5% (Range: 0.3 – 4.9%). Descriptive statistics (mean ± SD) for all variables in addition to mean differences between men and women and effect sizes are provided in Table 2. The men achieved significantly shorter sprint times, a greater maximum velocity and greater sprint mechanical properties with all effects being very large. No significant differences were found for any of the hop variables between men and women with effects considered trivial. Drop jump RSI and JH were significantly greater in men with moderate effect sizes. A small but non-significant effect was found in drop jump CT. Significantly greater IMTP PF and relative PF were found in men compared with women with effects considered large and moderate respectively.
Table 4.1: Test-retest single measure intraclass correlation coefficient with 95% CI and CV% for sprint, hop, drop jump and isometric mid-thigh pull for men and women.

<table>
<thead>
<tr>
<th></th>
<th>Men</th>
<th></th>
<th>Women</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICC</td>
<td>CV%</td>
<td>ICC</td>
<td>CV%</td>
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<td></td>
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<tr>
<td>Sprint Performance</td>
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</tr>
<tr>
<td>0-10 m (s)</td>
<td>0.93</td>
<td>0.7 (0.78 to 0.98)</td>
<td>0.99</td>
<td>0.6 (0.96 to 0.99)</td>
</tr>
<tr>
<td>10-20 m (s)</td>
<td>0.93</td>
<td>0.8 (0.81 to 0.98)</td>
<td>0.98</td>
<td>0.6 (0.94 to 0.99)</td>
</tr>
<tr>
<td>20-30 m (s)</td>
<td>0.96</td>
<td>0.6 (0.87 to 0.99)</td>
<td>0.99</td>
<td>0.5 (0.97 to 0.99)</td>
</tr>
<tr>
<td>30-40 m (s)</td>
<td>0.98</td>
<td>0.6 (0.94 to 0.99)</td>
<td>0.99</td>
<td>0.4 (0.99 to 0.99)</td>
</tr>
<tr>
<td>40 m (s)</td>
<td>0.98</td>
<td>0.4 (0.95 to 0.99)</td>
<td>0.99</td>
<td>0.3 (0.99 to 0.99)</td>
</tr>
<tr>
<td>Max Velocity (m·s⁻¹)</td>
<td>0.98</td>
<td>0.5 (0.95 to 0.99)</td>
<td>0.99</td>
<td>0.4 (0.99 to 0.99)</td>
</tr>
<tr>
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<tr>
<td>Sprint Mechanical</td>
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<tr>
<td>Properties</td>
<td></td>
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</tr>
<tr>
<td>$F_0$ (N)</td>
<td>0.87</td>
<td>2.2 (0.65 to 0.96)</td>
<td>0.96</td>
<td>1.9 (0.87 to 0.99)</td>
</tr>
<tr>
<td>$P_{max}$ (W)</td>
<td>0.93</td>
<td>1.9 (0.80 to 0.98)</td>
<td>0.99</td>
<td>1.7 (0.96 to 0.99)</td>
</tr>
<tr>
<td>$v_0$ (m·s⁻¹)</td>
<td>0.98</td>
<td>0.5 (0.95 to 0.99)</td>
<td>0.99</td>
<td>0.4 (0.99 to 0.99)</td>
</tr>
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<td></td>
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</tr>
<tr>
<td>Hop</td>
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</tr>
<tr>
<td>CT (s)</td>
<td>0.96</td>
<td>2.4 (0.87 to 0.99)</td>
<td>0.95</td>
<td>2.4 (0.85 to 0.98)</td>
</tr>
<tr>
<td>JH (m)</td>
<td>0.96</td>
<td>2.1 (0.87 to 0.99)</td>
<td>0.94</td>
<td>2.3 (0.82 to 0.98)</td>
</tr>
<tr>
<td>RSI (m·s⁻¹)</td>
<td>0.95</td>
<td>4.6 (0.84 to 0.98)</td>
<td>0.95</td>
<td>4.8 (0.86 to 0.98)</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>Drop Jump</td>
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</tr>
<tr>
<td>CT (s)</td>
<td>0.94</td>
<td>3.9 (0.83 – 0.98)</td>
<td>0.96</td>
<td>3.4 (0.88 – 0.99)</td>
</tr>
<tr>
<td>JH (m)</td>
<td>0.96</td>
<td>2.8 (0.89 – 0.99)</td>
<td>0.95</td>
<td>4.5 (0.85 – 0.98)</td>
</tr>
<tr>
<td>RSI (m·s⁻¹)</td>
<td>0.98</td>
<td>2.9 (0.94 – 0.99)</td>
<td>0.95</td>
<td>4.9 (0.85 – 0.98)</td>
</tr>
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<td></td>
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<tr>
<td>Isometric Mid-Thigh Pull</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>PF (N)</td>
<td>0.96</td>
<td>3.7 (0.87 – 0.99)</td>
<td>0.97</td>
<td>3.4 (0.90 – 0.99)</td>
</tr>
<tr>
<td>Rel PF (N·kg⁻¹)</td>
<td>0.95</td>
<td>3.8 (0.86 – 0.99)</td>
<td>0.94</td>
<td>3.4 (0.89 – 0.99)</td>
</tr>
</tbody>
</table>

$F_0$ = Maximal theoretical horizontal force relative to body mass, $v_0$ = Maximal theoretical horizontal velocity,

CT = Contact time, JH = Jump height, RSI = Reactive strength index,

PF = Peak force, Rel PF = Peak force relative to body mass.
Table 4.2: Mean ± SD, mean difference with 95% CI, Cohen’s d effect size and magnitude for sprint, drop jump, hop and isometric mid-thigh pull.

<table>
<thead>
<tr>
<th></th>
<th>Men</th>
<th>Women</th>
<th>Mean Difference (95% CI)</th>
<th>p Value</th>
<th>Effect Size (95% CI)</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10 m (s)</td>
<td>1.90 ± 0.05</td>
<td>2.11 ± 0.10</td>
<td>-0.21 (-0.28 to -0.15)</td>
<td>&lt; 0.001**</td>
<td>-2.60 (-3.40 to -1.81)</td>
<td>Very large</td>
</tr>
<tr>
<td>10-20 m (s)</td>
<td>1.18 ± 0.04</td>
<td>1.32 ± 0.06</td>
<td>-0.15 (-0.18 to -0.11)</td>
<td>&lt; 0.001**</td>
<td>-3.08 (-3.86 to -2.30)</td>
<td>Very large</td>
</tr>
<tr>
<td>20-30 m (s)</td>
<td>1.09 ± 0.03</td>
<td>1.24 ± 0.06</td>
<td>-0.15 (-0.19 to -0.11)</td>
<td>&lt; 0.001**</td>
<td>-3.01 (-3.80 to -2.21)</td>
<td>Very large</td>
</tr>
<tr>
<td>30-40 m (s)</td>
<td>1.06 ± 0.05</td>
<td>1.23 ± 0.07</td>
<td>-0.17 (-0.21 to -0.12)</td>
<td>&lt; 0.001**</td>
<td>-2.66 (-3.45 to -1.88)</td>
<td>Very large</td>
</tr>
<tr>
<td>40 m (s)</td>
<td>5.22 ± 0.15</td>
<td>5.90 ± 0.29</td>
<td>-0.68 (-0.86 to -0.50)</td>
<td>&lt; 0.001**</td>
<td>-2.97 (-3.76 to -2.17)</td>
<td>Very large</td>
</tr>
<tr>
<td>Max Velocity (m.s⁻¹)</td>
<td>9.49 ± 0.40</td>
<td>8.23 ± 0.46</td>
<td>1.26 (0.92 to 1.59)</td>
<td>&lt; 0.001**</td>
<td>-2.93 (-3.70 to -2.15)</td>
<td>Very large</td>
</tr>
<tr>
<td>F₀ (N/kg)</td>
<td>9.3 ± 0.5</td>
<td>8.0 ± 0.7</td>
<td>1.4 (0.9 to 1.9)</td>
<td>&lt; 0.001**</td>
<td>-2.14 (-2.92 to -1.36)</td>
<td>Very large</td>
</tr>
<tr>
<td>Pₘₕₑₓ (W·kg⁻¹)</td>
<td>22.5 ± 2.6</td>
<td>16.4 ± 2.3</td>
<td>6.1 (4.2 to 8.0)</td>
<td>&lt; 0.001**</td>
<td>-2.50 (-3.28 to -1.72)</td>
<td>Very large</td>
</tr>
<tr>
<td>v₀ (m.s⁻¹)</td>
<td>9.84 ± 0.40</td>
<td>8.51 ± 0.46</td>
<td>1.33 (1.00 to 1.67)</td>
<td>&lt; 0.001**</td>
<td>-3.12 (-3.89 to -2.34)</td>
<td>Very large</td>
</tr>
<tr>
<td>Hop CT (s)</td>
<td>0.157 ± 0.019</td>
<td>0.158 ± 0.015</td>
<td>-0.001 (-0.014 to 0.012)</td>
<td>0.885</td>
<td>-0.06 (-0.73 to 0.84)</td>
<td>Trivial</td>
</tr>
<tr>
<td>Hop JH (m)</td>
<td>0.111 ± 0.015</td>
<td>0.111 ± 0.010</td>
<td>0.000 (-0.010 to 0.010)</td>
<td>0.954</td>
<td>-0.02 (-0.76 to 0.81)</td>
<td>Trivial</td>
</tr>
<tr>
<td>Hop RSI (m.s⁻¹)</td>
<td>0.72 ± 0.16</td>
<td>0.72 ± 0.13</td>
<td>0.00 (-0.11 to 0.11)</td>
<td>0.969</td>
<td>-0.01 (-0.79 to 0.76)</td>
<td>Trivial</td>
</tr>
<tr>
<td>DJ CT (s)</td>
<td>0.170 ± 0.028</td>
<td>0.183 ± 0.028</td>
<td>-0.013 (-0.035 to 0.008)</td>
<td>0.220</td>
<td>-0.47 (-1.25 to 0.30)</td>
<td>Small</td>
</tr>
<tr>
<td>DJ JH (m)</td>
<td>0.340 ± 0.049</td>
<td>0.296 ± 0.057</td>
<td>0.044 (0.003 to 0.086)</td>
<td>0.038*</td>
<td>0.83 (0.05 to 1.60)</td>
<td>Moderate</td>
</tr>
<tr>
<td>DJ RSI (m.s⁻¹)</td>
<td>2.06 ± 0.43</td>
<td>1.65 ± 0.35</td>
<td>0.41 (0.10 to 0.71)</td>
<td>0.011*</td>
<td>1.04 (0.26 to 1.82)</td>
<td>Moderate</td>
</tr>
<tr>
<td>IMTP PF (N)</td>
<td>2642 ± 437</td>
<td>1913 ± 342</td>
<td>730 (425 to 1034)</td>
<td>&lt; 0.001**</td>
<td>1.86 (1.08 to 2.64)</td>
<td>Large</td>
</tr>
<tr>
<td>IMTP Relative PF (N·kg⁻¹)</td>
<td>36.3 ± 6.2</td>
<td>29.8 ± 5.2</td>
<td>6.49 (2.0 to 10.9)</td>
<td>0.006**</td>
<td>1.13 (0.35 to 1.91)</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

F₀ = Maximal theoretical horizontal force relative to body mass, v₀ = Maximal theoretical horizontal velocity, CT = Contact time, JH = Jump height, RSI = Reactive strength index, DJ = drop jump, IMTP = Isometric mid-thigh pull, PF = Peak force, Relative PF = Peak force relative to body mass.

* p<0.05, ** p <0.01
Correlations between sprint performance variables and sprint mechanical properties and Hop RSI, DJ RSI, IMTP PF and IMTP relative PF and are shown in Table 4.3 and Table 4.4 respectively. No significant correlations were found between hop RSI, drop jump RSI, IMTP PF or relative PF and any of the sprint performance measures. A significant strong positive correlation was found between IMTP PF and relative $P_{\text{max}}$ in men only.

Table 4.3: Inter-correlation matrix between drop jump and hop RSI, isometric mid-thigh pull PF and relative PF and sprint performance measures in men (top) and women (bottom). Results are presented as $r$ (95% CI) with statistically significant correlations presented in bold.

<table>
<thead>
<tr>
<th></th>
<th>0-10 m (s)</th>
<th>10-20 m (s)</th>
<th>20-30 m (s)</th>
<th>30-40 m (s)</th>
<th>40 m (s)</th>
<th>Max Velocity (m·s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hop RSI (m·s$^{-1}$)</td>
<td>-0.22</td>
<td>-0.15</td>
<td>-0.22</td>
<td>-0.17</td>
<td>-0.21</td>
<td>0.22</td>
</tr>
<tr>
<td>(95% CI)</td>
<td>(-0.67 to 0.35)</td>
<td>(-0.63 to 0.42)</td>
<td>(-0.67 to 0.35)</td>
<td>(-0.65 to 0.39)</td>
<td>(-0.67 to 0.36)</td>
<td>(-0.35 to 0.67)</td>
</tr>
<tr>
<td>Drop Jump RSI (m·s$^{-1}$)</td>
<td>-0.03</td>
<td>0.01</td>
<td>0.14</td>
<td>-0.02</td>
<td>0.02</td>
<td>0.10</td>
</tr>
<tr>
<td>(95% CI)</td>
<td>(-0.55 to 0.51)</td>
<td>(-0.52 to 0.54)</td>
<td>(-0.42 to 0.62)</td>
<td>(-0.55 to 0.51)</td>
<td>(-0.52 to 0.54)</td>
<td>(-0.46 to 0.60)</td>
</tr>
<tr>
<td>IMTP PF (N)</td>
<td>-0.31</td>
<td>-0.40</td>
<td>-0.47</td>
<td>-0.35</td>
<td>-0.42</td>
<td>0.30</td>
</tr>
<tr>
<td>(95% CI)</td>
<td>(-0.72 to 0.26)</td>
<td>(-0.77 to 0.16)</td>
<td>(-0.80 to 0.08)</td>
<td>(-0.74 to 0.22)</td>
<td>(-0.78 to 0.14)</td>
<td>(-0.27 to 0.72)</td>
</tr>
<tr>
<td>IMTP PF (N·kg$^{-1}$)</td>
<td>-0.31</td>
<td>-0.29</td>
<td>-0.24</td>
<td>-0.22</td>
<td>-0.30</td>
<td>0.21</td>
</tr>
<tr>
<td>(95% CI)</td>
<td>(-0.72 to 0.26)</td>
<td>(-0.71 to 0.29)</td>
<td>(-0.68 to 0.34)</td>
<td>(-0.67 to 0.35)</td>
<td>(-0.71 to 0.28)</td>
<td>(-0.36 to 0.67)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>0-10 m (s)</th>
<th>10-20 m (s)</th>
<th>20-30 m (s)</th>
<th>30-40 m (s)</th>
<th>40 m (s)</th>
<th>Max Velocity (m·s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hop RSI (m·s$^{-1}$)</td>
<td>-0.34</td>
<td>-0.16</td>
<td>-0.31</td>
<td>-0.22</td>
<td>-0.28</td>
<td>0.27</td>
</tr>
<tr>
<td>(95% CI)</td>
<td>(-0.74 to 0.23)</td>
<td>(-0.64 to 0.40)</td>
<td>(-0.72 to 0.27)</td>
<td>(-0.67 to 0.35)</td>
<td>(-0.71 to 0.29)</td>
<td>(-0.30 to 0.70)</td>
</tr>
<tr>
<td>Drop Jump RSI (m·s$^{-1}$)</td>
<td>-0.04</td>
<td>0.21</td>
<td>0.02</td>
<td>0.04</td>
<td>0.04</td>
<td>-0.03</td>
</tr>
<tr>
<td>(95% CI)</td>
<td>(-0.56 to 0.50)</td>
<td>(-0.36 to 0.67)</td>
<td>(-0.51 to 0.55)</td>
<td>(-0.50 to 0.56)</td>
<td>(-0.50 to 0.56)</td>
<td>(-0.55 to 0.51)</td>
</tr>
<tr>
<td>IMTP PF (N)</td>
<td>0.30</td>
<td>0.13</td>
<td>0.29</td>
<td>0.36</td>
<td>0.29</td>
<td>-0.36</td>
</tr>
<tr>
<td>(95% CI)</td>
<td>(-0.27 to 0.72)</td>
<td>(-0.43 to 0.62)</td>
<td>(-0.29 to 0.71)</td>
<td>(-0.21 to 0.75)</td>
<td>(-0.28 to 0.71)</td>
<td>(-0.75 to 0.21)</td>
</tr>
<tr>
<td>IMTP PF (N·kg$^{-1}$)</td>
<td>0.09</td>
<td>0.01</td>
<td>0.11</td>
<td>0.28</td>
<td>0.13</td>
<td>-0.24</td>
</tr>
<tr>
<td>(95% CI)</td>
<td>(-0.45 to 0.59)</td>
<td>(-0.52 to 0.54)</td>
<td>(-0.45 to 0.61)</td>
<td>(-0.30 to 0.71)</td>
<td>(-0.43 to 0.62)</td>
<td>(-0.68 to 0.34)</td>
</tr>
</tbody>
</table>

RSI = Reactive strength index, IMTP = Isometric mid-thigh pull,
PF = Peak force, Rel PF = Peak force relative to body mass.
Table 4.4: Inter-correlation matrix between drop jump and hop RSI, isometric mid-thigh pull PF and relative PF and sprint mechanical properties in men (top) and women (bottom). Results are presented as r (95% CI) with statistically significant correlations presented in bold.

<table>
<thead>
<tr>
<th></th>
<th>Men</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F_0$ (N·kg$^{-1}$)</td>
<td>$P_{max}$ (W·kg$^{-1}$)</td>
<td>$v_0$ (m·s$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>Hop RSI (m·s$^{-1}$)</td>
<td>0.07</td>
<td>0.15</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>DJ RSI (m·s$^{-1}$)</td>
<td>-0.11</td>
<td>-0.23</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>IMTP PF (N)</td>
<td>0.23</td>
<td>0.61</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>IMTP Rel PF (N·kg$^{-1}$)</td>
<td>0.24</td>
<td>0.37</td>
<td>0.24</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Women</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F_0$ (N·kg$^{-1}$)</td>
<td>$P_{max}$ (W·kg$^{-1}$)</td>
<td>$v_0$ (m·s$^{-1}$)</td>
</tr>
<tr>
<td>Hop RSI (m·s$^{-1}$)</td>
<td>0.34</td>
<td>0.32</td>
<td>0.24</td>
</tr>
<tr>
<td>DJ RSI (m·s$^{-1}$)</td>
<td>0.03</td>
<td>0.00</td>
<td>0.07</td>
</tr>
<tr>
<td>IMTP PF (N)</td>
<td>-0.13</td>
<td>-0.27</td>
<td>-0.33</td>
</tr>
<tr>
<td>IMTP Rel PF (N·kg$^{-1}$)</td>
<td>0.05</td>
<td>-0.04</td>
<td>-0.22</td>
</tr>
</tbody>
</table>

RSI = Reactive strength index, IMTP = Isometric mid-thigh pull, PF = Peak force
Rel PF = Peak force relative to body mass, $F_0$ = Maximal theoretical horizontal force relative to body mass
$v_0$ = Maximal theoretical horizontal velocity

The relationships between hop, DJ and IMTP measures for both men and women are shown in Table 4.5. DJ CT had a very large significant correlation with Hop CT, Hop JH and Hop RSI in men only. DJ RSI had a significant correlation with Hop CT (men: large negative, women: very large negative), Hop JH (men: large positive, women: very large positive) and Hop RSI (men and women: large positive). IMTP relative PF had a significant correlation with Hop CT (men: large negative), Hop JH (men: large positive) and Hop RSI (men: very large positive) and IMTP PF (men and women: very large positive).
Table 4.5: Inter-correlation matrix between hop, drop jump and IMTP measures in men (top) and women (bottom). Results are presented as r (95% CI) with statistically significant correlations presented in bold.

<table>
<thead>
<tr>
<th></th>
<th>DJ CT (s)</th>
<th>Hop CT (s)</th>
<th>Hop JH (m)</th>
<th>Hop RSI (m·s(^{-1}))</th>
<th>IMTP PF (N)</th>
<th>IMTP Rel PF (N·kg(^{-1}))</th>
<th>Hop CT (s)</th>
<th>Hop JH (m)</th>
<th>Hop RSI (m·s(^{-1}))</th>
<th>IMTP PF (N)</th>
<th>IMTP Rel PF (N·kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hop CT (s)</td>
<td>0.84</td>
<td>(0.55 to 0.95)</td>
<td>-0.77</td>
<td>(-0.92 to -0.39)</td>
<td>-0.77</td>
<td>(-0.31 to 0.5)</td>
<td>0.01</td>
<td>(-0.52 to 0.54)</td>
<td>(-0.92 to -0.41)</td>
<td>0.34</td>
<td>(0.60 to 0.95)</td>
</tr>
<tr>
<td>DJ JH (m)</td>
<td>-0.19</td>
<td>(-0.65 to 0.38)</td>
<td>0.24</td>
<td>(0.15 to 0.87)</td>
<td>0.19</td>
<td>-0.38</td>
<td>0.19</td>
<td>(0.31 to 0.90)</td>
<td>(0.20 to 0.88)</td>
<td>0.01</td>
<td>0.92</td>
</tr>
<tr>
<td>DJ RSI (m·s(^{-1}))</td>
<td>-0.63</td>
<td>(-0.87 to -0.14)</td>
<td>0.63</td>
<td>(-0.09 to 0.80)</td>
<td>0.62</td>
<td>(0.34 to 0.74)</td>
<td>0.34</td>
<td>(-0.54 to 0.52)</td>
<td>(0.14 to 0.87)</td>
<td>0.02</td>
<td>0.77</td>
</tr>
<tr>
<td>IMTP PF (N)</td>
<td>-0.39</td>
<td>(-0.76 to 0.18)</td>
<td>0.47</td>
<td>(-0.08 to 0.80)</td>
<td>0.46</td>
<td>0.86</td>
<td>0.31</td>
<td>(-0.30 to 0.70)</td>
<td>(-0.09 to 0.80)</td>
<td>1</td>
<td>0.92</td>
</tr>
<tr>
<td>IMTP Rel PF (N·kg(^{-1}))</td>
<td>-0.65</td>
<td>(-0.88 to -0.18)</td>
<td>0.68</td>
<td>(0.23 to 0.89)</td>
<td>0.74</td>
<td>1</td>
<td>0.31</td>
<td>(-0.54 to 0.52)</td>
<td>(-0.87 to -0.14)</td>
<td>0.86</td>
<td>0.92</td>
</tr>
</tbody>
</table>

CT = Contact time, JH = Jump Height, RSI = Reactive strength index, DJ = Drop jump
IMTP = Isometric mid-thigh pull, PF = Peak force, Rel PF = Peak force relative to body mass.

4.4 Discussion
The present study found no significant relationships between drop jump RSI and sprint performance or sprint mechanical properties in both men and women. In contrast, research in male sprinters by Smirniotou et al. (2008) and female sprinters by Hennessy and Kilty (2001) found significant correlations with sprint acceleration performance over 10, 30 and 60 m. Young et al. (1995) found no relationship with drop jump RSI and sprint performance over 2.5 m and 50 m. The authors, Young et al. (1995), suggested that the sprint athletes studied
may not have been able to tolerate the stretch loads imposed on them during the drop jump test. This may have been the case in the current study as evidenced by the large range of drop jump CTs (men: 0.137 - 0.249 s, women: 0.144 - 0.227 s) suggesting a wide range of stiffness capabilities (Arampatzis et al. 2001a). It is likely that drop jump RSI may therefore be a poor indicator of fast SSC performance in groups with wide ranging physical capacities i.e. leg spring stiffness; Chapter 6 will investigate this further. Additionally, the ground contact times of the drop jumps in the study were much larger than those observed during the acceleration (~0.130 s) and transition phase (0.110 – 0.119 s) in male and female sprint athletes of a similar level (Debaere et al. 2013b).

Similar to drop jumps, no significant relationship was found between hop RSI and any of the sprint performance or sprint mechanical variables. By contrast, Nagahara et al. (2014), found a relationship between hop RSI and 60 m sprint time, but did not impose a set hopping frequency on the athletes. Previously, Chelly and Dennis (2001) used a set hopping frequency (2.0 Hz) and found a large positive correlation (r = 0.68) between stiffness and maximal sprinting velocity. Stiffness measures are considered indicative of an athlete’s ability to tolerate stretch loads and thus achieve shorter CTs (Arampatzis et al. 2001a). The 2.2 Hz frequency used in the present study resulted in the hopping test becoming a sub-maximal reactive strength test as athletes limited their jump height in order to maintain the required hopping rhythm. For this reason, RSI measured in sub-maximal hopping would not reflect an athlete’s true ability to generate an impulse and therefore constrained hopping is not recommended.

Neither of the IMTP measures was significantly related to any of the sprint performance measures. This is in contrast to Thomas et al. (2015) and West et al. (2011) who focused on short acceleration (20 m) but is in agreement with Wang et al. (2016) who assessed longer sprints (40 m). Several key differences exist between those studies and the current study due to the different populations (sprinters versus team sport players) and different starting procedures used (block starts versus standing starts). A block start requires substantially greater technical ability in addition to the need to apply optimal levels of vertical and horizontal force (Salo and Bezodis 2004). For the sprint mechanical properties, PF had a significant and large positive correlation with $P_{\text{max}}$ in men with no other significant relationships found. While this may suggest that higher levels of absolute maximum strength may afford higher levels of horizontal power in sprinting, this is not supported by the results
of the female group and therefore further research is required before a fully informed conclusion can be made.

It is important to note that all the strength tests used in this investigation were performed vertically with no horizontal component and this may partially explain the lack of significant findings in the current sprinter sample. Weyand et al. (2000) found that faster maximum velocities were achieved predominantly through the application of greater vertical forces (relative to mass) on the ground at very short CTs (~0.100 s). Subsequent research by Weyand et al. (2010) found that the stance phase limit to achieving higher maximum velocities is imposed by the minimum time required to apply great mass-specific forces and not the maximum force the limb can apply to the ground. Consequently, the duration of contact phases during sprinting are not long enough for maximal force production by the lower limb extensor muscles. The durations of force production in drop jumps, hopping and especially in the IMTP were considerably longer than those observed at high velocity sprinting.

The ability to effectively direct the horizontal component of GRF has been shown to be a key factor in sprint performance. Morin et al. (2012) found that the magnitude of the resultant force was not related to 100 m performance but the ability to direct the action force backwards against the ground i.e. horizontal force application, was important. In accordance with this, Rabita et al. (2015) found that neither the resultant GRF nor the vertical component were significantly correlated to sprint performance over 40 m. The authors suggested that the ability to generate high net horizontal force at high velocity was more important for sprint acceleration than simply increasing the magnitude of the resultant GRF. The maximal strength and reactive strength tests in the current study did not examine the athletes’ technical abilities to apply force and therefore the impact of technique on force management could not be evaluated.

Differences in sprint performance and mechanical properties between sexes have been well established in the literature and are consistent with the results of this study. Men generally achieve faster sprint times due to greater levels of maximal velocity, greater levels of horizontal force and power, longer acceleration distances, longer step lengths and shorter CTs (Debaere et al. 2013b; Slawinski et al. 2017). Higher $P_{\text{max}}$ and $F_0$ are likely due to higher muscle mass and larger muscle fiber cross-sectional areas enabling a greater ability to produce force rapidly (Cheuvront et al. 2005). Furthermore, these differences likely explain
the significantly higher IMTP PF and relative PF observed in men in the current study. The significant differences in drop jump RSI can be largely attributed to the men attaining moderately higher JHs as differences in CT were considered small and non-significant.

No significant sex differences were found in any of the hop variables with CT, JH and RSI being near identical in men and women. This can be explained by the imposition of a set hopping frequency inducing an unintended limit on possible RSI scores. A frequency of 2.2 Hz constrains total hop time (contact and flight time) to a sum of 0.455 s, therefore the flight time, which is used to calculate JH, is limited based on the duration of the preceding CT. For example, a hop with a CT of 0.140 would only permit a flight time of 0.315 s, yielding a JH limitation to 0.122 m. Shorter CTs are possible in hopping compared to drop jumps since the imposed stretch loads, which are determined by the athlete’s mass and the preceding hop height, are substantially lower. Consequently, the men and women were equally capable of tolerating the stretch loads and thus were equally limited in how high they could jump.

The results of this study indicated that hop CT, JH and RSI had large to very large correlations with drop jump RSI in both men and women and with IMTP relative PF in men. All three hop measures had a near perfect relationships with one another (absolute value of r: 0.91 – 0.99) and therefore any variable related to one hop variable would also be related to the remaining two. This suggests that higher drop jump RSI scores and higher relative PF values were associated with lower CTs in hopping and subsequently higher JHs and RSI scores. This highlights the potential role of the drop jump RSI and relative PF as indicators of an athlete’s ability to tolerate relatively low stretch loads in submaximal exercises.

No relationship was found in the current study between IMTP PF, relative PF and drop jump RSI in men or women. Barr and Nolte (2011) found a significant, moderate positive correlation between drop jump RSI (from 0.36 m) and 1RM front squat relative to body mass in female rugby players (r = 0.44). Additionally, Beattie et al. (2016) found a significant moderate positive correlation between drop jump RSI (from 0.30 m) and PF measured during an IMTP (r = 0.30) but no significant correlation between relative PF and RSI, however, the aforementioned studies did not assess sprint athletes. Both the male and female athletes in the current study had higher RSI values than the participants in Beattie et al. (2016) (Men: 2.06 ± 0.43, Women: 1.65 ± 0.35 versus: 1.37 ± 0.31) but considerably lower maximum strength scores (Men: 2642 ± 437 N, Women: 1913 ± 342 N versus 3578 ± 884 N). This highlights that high levels of maximum strength are not required to achieve high RSI scores. The higher
RSI scores found in the present sprint athletes were most likely achieved as a result of several years of sprint and plyometric training.

4.5 Conclusion
For practitioners who wish to assess reactive strength in hopping, it is recommended that the test activity should not be constrained by the imposition of a set hopping frequency. Practitioners and researchers are advised to use split times in addition to outcome measures for studies when investigating correlations because sprint performance is a multidimensional skill which requires a wide range of physical and technical demands. Furthermore, several methods of assessing reactive strength are needed that can better represent the demands present in the distinct phases of sprinting e.g. acceleration, maximum velocity and deceleration. Chapter 5 will investigate if reactive strength measures are affected by differences in athlete’s performance capabilities such as the wide ranging contact times observed in the current chapter. Finally, it is concluded that greater levels of RSI, as assessed during a 0.3 m drop jump, do not necessarily require high levels of maximum strength. Training modalities that utilize movements with CTs below 0.250 s such as sprinting or plyometrics are advised to enhance fast SSC performance.
Chapter 5: Reactive Strength Index: A Poor Indicator of Reactive Strength?

This chapter has been published in the following journal:
5.1 Introduction

The stretch shortening cycle (SSC) is utilised in many sporting movements e.g. in the leg extensor muscles during the ground contact phases of running, sprinting, jumping and hopping movements (Nicol et al. 2006). The SSC of muscle function has been characterised by an eccentric (lengthening) muscle action quickly followed by a concentric (shortening) muscle action. In this state, greater positive work and more power is generated during the concentric muscle action relative to that of an isolated concentric muscle action (Komi 2000). Several mechanisms have been proposed to explain the greater positive work performed by the muscle: an increase in the time available to develop force, the storage and subsequent utilisation of elastic energy in the series elastic element of a muscle fibre, force potentiation from individual cross-bridges and the stretch reflex i.e. the capacity of additional sensory feedback to enhance the activation of motor neurons during concentric muscle action (Enoka 2015). The relative contribution of each potential mechanism will vary across movement type as factors such as tendon loading and SSC duration are not identical in all SSC activities (Komi 2000). Therefore, generalisations about the SSC should not be made from one specific muscle and from one condition only (Komi 2003).

Direct methods using in vivo force measurements have been employed to characterise SSC function in isolated muscles during human locomotion. Based on these methods, three fundamental conditions have been identified for effective SSC function: a well-timed pre-activation of the muscle prior to impact, a short and fast eccentric phase and a near immediate transition between eccentric and concentric phases (Komi and Gollhofer 1997; Nicol et al. 2006; Enoka 2015). Consequently, coaches have attempted to evaluate specific sports movements which utilise the SSC. To accomplish this, the concept of reactive strength was developed (Young 1995). Reactive strength has been described in numerous ways throughout the literature with the most commonly used definition being the capacity of an athlete to bear a stretch load and subsequently switch rapidly from an eccentric to concentric muscle action (Newton and Dugan 2002). Other authors have focussed on a more mechanical definition i.e. an athlete’s ability to rapidly generate force under high eccentric load (Lockie et al. 2015). Regardless, reactive strength has been assessed during various sports movements e.g. drop jumps, vertical hops, rebound jumps and countermovement jumps.

Within the literature SSCs have been generally classified as either fast or slow based on contact times (CTs) < 0.250 s and > 0.250 s, respectively (Schmidtbleicher 1992). The
current chapter exclusively examines reactive strength as assessed during a fast SSC movement, i.e. the drop jump where, an athlete drops from a set height and upon landing performs a vertical jump at maximal effort. The drop jump can be broken into two distinct temporal phases, the contact phase, which can be further sub divided into landing time ($T_{\text{Landing}}$) and push off time ($T_{\text{Push}}$), and the flight phase i.e. time spent in the air. The manipulation of these two temporal phases has led to the identification of three drop jump techniques. The bounce drop jump, where an athlete attempts to minimise CT which occurs at the expense of higher JHs; the countermovement drop jump, where an athlete attempts to achieve maximal flight time (FT) and thus maximal jump height which results in much longer CTs than the aforementioned method; and the combination technique which was employed in Chapter 4, whereby an athlete attempts to get off the ground as quickly as possible while also aiming to jump as high as possible (Bobbert et al. 1987; Young et al. 1995).

It has been suggested that reactive strength can be assessed in the drop jump using the reactive strength index (RSI) performed using the combination technique (Newton and Dugan 2002). Several authors have proposed that the RSI is an effective means of assessing the performance of a SSC task and can also provide an indication of an athlete’s vertical stiffness ($K_{\text{vert}}$) (Flanagan and Comyns 2008; Kipp et al. 2017). However, Chapter 4 found that RSI, measured during a 0.3 m drop jump, was not significantly correlated to a range of sprint performance measures over 40 m. It was suggested that differences in athlete’s performance capabilities i.e. leg spring stiffness, may have had an affect on the ability of RSI to assess reactive strength. Within the literature, RSI has been calculated using two calculation methods: the jump height (JH) in a drop jump, generally derived from flight time (FT), divided by the CT or alternatively the FT of the jump divided by the CT (Young 1995; Markwick et al. 2015). The latter method has sometimes been referred to as the flight to contact time ratio or simply the reactive strength ratio (RSR). The key distinctions between RSI and RSR values, from a calculation perspective, are highlighted in Table 5.1 below. The differences between RSI and RSR values as performance metrics have yet to be determined.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Unit</th>
<th>Calculation</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactive Strength Index</td>
<td>m·s$^{-1}$</td>
<td>Jump Height / Contact Time</td>
<td>A theoretical quantity that represents the predicted jump height that would be achieved with a ground contact time of one second</td>
</tr>
<tr>
<td>Reactive Strength Ratio</td>
<td>Unitless</td>
<td>Flight Time / Contact Time</td>
<td>The ratio of flight time to contact time</td>
</tr>
</tbody>
</table>
The purpose of the current study was to assess the relationship between RSI and RSR and assess the relationship between RSI, RSR values and other kinematic and kinetic drop jump variables. Finally, we aimed to highlight problems with the use of both RSI and RSR as performance metrics using examples from two groups of sprint athletes. We hypothesized that both RSI and RSR would be correlated to the common variables used in their calculation i.e. CT and FT, but the strength of these correlations would differ due to differences in drop jump performance strategy. Additionally, we hypothesized that individual athletes in both the male and female group would achieve similar RSI or RSR scores through different combinations of CT and JH values.

5.2 Methods

5.2.1 Athletes

Twenty eight athletes, involved with sprint and hurdle events (IAAF Scoring Tables points range, Men: 731 - 1233 points, Women: 878 - 1128 points), consisting of fourteen males (mean ± SD, age: 22 ± 2 years; body height: 1.83 ± 0.06 m; body mass: 72.1 ± 6.5 kg) and fourteen females (mean ± SD, age: 22 ± 4 years; body height: 1.72 ± 0.07 m; body mass: 64.4 ± 4.6 kg) agreed to participate in this investigation. Fourteen of the athletes competed regularly at an international level (seven men and seven women) whereas the remaining fourteen athletes competed regularly at a national level (seven men and seven women). Ethical approval was provided by the Institution’s Research Ethics Committee and written consent forms were completed by all athletes prior to testing in compliance with the Declaration of Helsinki.

5.2.2 Design

This cross-sectional study was designed to assess the relationship between bilateral drop jump variables (RSI, RSR, CT, T_{Landing}, T_{Push}, FT, JH and K_{vert}) in males and females with all drop jumps performed in a biomechanics laboratory. All athletes had at least two years of experience performing plyometric exercises and were well accustomed to performing drop jumps as part of their monitoring programme.
5.2.3 Methodology

Following a standardised dynamic warm up, athletes performed three maximal effort drop jumps with the first jump serving as a practice trial and the two subsequent jumps retained for analysis. Athletes were instructed to keep their hands on their hips throughout the entire movement, to step directly off of the box i.e. avoid stepping down from the box or jumping off of the box, avoid any tucking motion in the air, to land in the same position as take-off and to aim to minimise CT while also trying to maximise JH (Young et al. 1995). All drop jumps and drop jump force-time traces were visually assessed by the experimenter and trials were repeated if any of the instructions were not followed, if CT > 0.250 s or if the force-time trace contained initial impact transients i.e. force peaks. Thirty seconds of rest were provided between trials to avoid any deleterious effects of fatigue on performance (Read and Cisar 2001). Drop jumps were performed from a box height of 0.3 m with athletes landing on an AMTI NET force platform (Watertown, MA, USA) operating at 1,000 Hz.

The dependent variables were: CT, T_{Land}, T_{Push}, FT, JH, RSI, RSR and K_{vert}. CTs and FTs were obtained directly from the force-time trace using a threshold of >10 N to determine contact and <10 N to determine flight. Flight time was subsequently used to estimate JH using an adapted version of the second mathematical equation of linear motion

\[ JH = FT^2 \times 1.22625 \]

This method of estimating JH assumes that an athlete’s centre of mass is the same on landing and take-off. Although athletes take-off with a fully extended knee and plantar-flexed ankle they may not land in a plantar-flexed position and therefore the centre of mass may be lower at landing than at take-off. This would result in an amplification of FT and thus errors in the subsequent calculation of JH. The instructions given to the athletes aimed to minimise these errors as much as possible. RSI and RSR were calculated as JH divided by CT, and FT divided by CT respectively. T_{Land} was calculated similar to previous investigations as the time elapsed between initial contact to the instant of maximal vertical displacement of the centre of mass (McNitt-Gray 1991; Makaruk et al. 2014). T_{Push} was calculated as CT minus T_{Land}. K_{vert} was calculated as the peak vertical ground reaction force divided by the maximum vertical displacement of the centre of mass (McMahon and Cheng 1990). Peak vertical ground reaction force was obtained directly from the landing phase of the force-time trace and vertical displacement was calculated through double integration of the vertical component of the ground reaction force (Street et al. 2001; Kipp et al. 2017). Initial landing
velocity was derived using an adapted version of the fourth mathematical equation of linear motion:

\[
\text{Landing velocity} = \sqrt{2 \times g \times \text{Drop Height}}.
\]

To adjust for mass differences, \( K_{\text{vert}} \) values were reported relative to body mass (Farley et al. 1993; Maloney et al. 2015). Similarly to previous investigations, the correlation coefficients between vertical force and vertical displacement were calculated for each trial, with all correlations > 0.9, to ensure the efficacy of spring-mass model (Padua et al. 2005; Maloney et al. 2015).

The reliability of each variable was assessed by calculating both the single measure intraclass correlation coefficient (ICC) and typical error, expressed as a coefficient of variation (CV%) (Hopkins et al. 2009). The ICC was above > 0.9 (Range: 0.902 – 0.976) and the CV% was below 8% (1.7 – 7.4%) for all variables.

5.2.4 Statistical Analyses

Descriptive statistics for all variables were presented as mean ± SD. All variables were deemed to be normally distributed as the Shapiro-Wilk’s test was found to have an alpha level > 0.05. Relationships between drop jump measures were determined using Pearson’s product moment correlation. As multiple correlations were performed, a false discovery rate controlling procedure was used to account for the familywise error rate resulting in an alpha level for significance set at 0.0286 (Benjamini and Hochberg 1995). The strength of the correlations was evaluated as s: trivial (0 – 0.09), small (0.1 – 0.29), moderate (0.3 – 0.49), large (0.5 – 0.69), very large (0.7 – 0.89), near perfect (0.9 – 0.99) and perfect (1) (Hopkins et al. 2009). Non-significant correlations were not interpreted. All statistical analyses were performed using SPSS software (version 21.0, SPSS, Inc., IL, USA).

Between / Within Athlete Analysis

To highlight the variable nature of reactive strength measures, between-athlete differences in drop jump dependent variables (expressed as a %) were calculated in instances where athletes had near identical RSI or RSR values. Within-athlete differences were also assessed in instances where an athlete achieved their highest RSI and RSR in separate trials.
5.3 Results
Descriptive statistics (mean ± SD) for all variables are given in Table 5.2. Inter-correlation matrices of drop jump measures are presented for men and women in Tables 5.3 and 5.4 respectively. Scatter plots illustrating the relationship between RSI and RSR and the key kinematic variables i.e. CT and JH, are presented in Figure 5.1 for male and female groups. Significant correlations were found between CT and RSI and RSR in men whereas CT was correlated to RSR only in women. JH was significantly correlated to RSI in men and women and RSR in men only.

Within-athlete differences for an exemplar athlete are given in Table 5.5 along with between-athlete differences from instances where athletes achieved near identical RSI or RSR values (Δ < 1%).

Table 5.2: Descriptive statistics (Mean ± SD) for drop jump variables.

<table>
<thead>
<tr>
<th></th>
<th>Men</th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Time (s)</td>
<td>0.164 ± 0.016</td>
<td>0.183 ± 0.028</td>
</tr>
<tr>
<td>Landing Time (s)</td>
<td>0.071 ± 0.011</td>
<td>0.081 ± 0.015</td>
</tr>
<tr>
<td>Push-off Time (s)</td>
<td>0.093 ± 0.008</td>
<td>0.102 ± 0.014</td>
</tr>
<tr>
<td>Flight Time (s)</td>
<td>0.516 ± 0.054</td>
<td>0.490 ± 0.046</td>
</tr>
<tr>
<td>Jump Height (m)</td>
<td>0.330 ± 0.067</td>
<td>0.296 ± 0.057</td>
</tr>
<tr>
<td>Reactive Strength Index (m.s⁻¹)</td>
<td>2.04 ± 0.49</td>
<td>1.65 ± 0.45</td>
</tr>
<tr>
<td>Reactive Strength Ratio</td>
<td>3.18 ± 0.52</td>
<td>2.73 ± 0.42</td>
</tr>
<tr>
<td>Vertical Leg Spring Stiffness (kN.m⁻¹.kg⁻¹)</td>
<td>0.648 ± 0.129</td>
<td>0.495 ± 0.211</td>
</tr>
</tbody>
</table>
Table 5.3: Inter-correlation matrix between drop jump variables in men. Results are presented as r (95% CI) with statistically significant correlations presented in bold.

<table>
<thead>
<tr>
<th></th>
<th>RSI (m.s(^{-1}))</th>
<th>RSR</th>
<th>CT (s)</th>
<th>T(_{\text{Land}}) (s)</th>
<th>T(_{\text{Push}}) (s)</th>
<th>FT (s)</th>
<th>JH (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSI (m.s(^{-1}))</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RSR</td>
<td>0.97** (0.91 to 0.99)</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.71** (-0.90 to -0.28)</td>
<td>-0.86** (-0.95 to -0.61)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT (s)</td>
<td>-0.85** (-0.95 to -0.7)</td>
<td>-0.91** (-0.97 to -0.74)</td>
<td>0.89** (0.68 to 0.96)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T(_{\text{Land}}) (s)</td>
<td>-0.28 (0.70 to 0.30)</td>
<td>-0.48 (0.81 to 0.07)</td>
<td>0.80** (0.46 to 0.93)</td>
<td>0.44 (0.12 to 0.79)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T(_{\text{Push}}) (s)</td>
<td>(0.78 to 0.98)</td>
<td>(0.50 to 0.94)</td>
<td>(-0.77 to 0.15)</td>
<td>(-0.88 to -0.19)</td>
<td>(-0.48 to 0.57)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FT (s)</td>
<td>0.93* 0.82** (0.78 to 0.97)</td>
<td>0.80** (0.46 to 0.93)</td>
<td>(-0.76 to 0.19)</td>
<td>(-0.87 to 0.15)</td>
<td>(-0.46 to 0.60)</td>
<td>0.10 (0.61)</td>
<td></td>
</tr>
<tr>
<td>JH (m)</td>
<td>0.78** (0.43 to 0.93)</td>
<td>0.87** (0.63 to 0.96)</td>
<td>-0.89** (-0.96 to -0.68)</td>
<td>(-0.98 to -0.82)</td>
<td>(-0.82 to 0.03)</td>
<td>(0.03 to 0.84)</td>
<td>(0.01 to 0.83)</td>
</tr>
<tr>
<td>(K_{\text{vert}}) (kN.m(^{-1}).kg(^{-1}))</td>
<td>(0.43 to 0.93)</td>
<td>(0.63 to 0.96)</td>
<td>(-0.96 to -0.68)</td>
<td>(-0.98 to -0.82)</td>
<td>(-0.82 to 0.03)</td>
<td>(0.03 to 0.84)</td>
<td>(0.01 to 0.83)</td>
</tr>
</tbody>
</table>

RSI = Reactive strength index, RSR = Reactive strength ratio, CT = Contact time, T\(_{\text{Land}}\) = Landing time, T\(_{\text{Push}}\) = Push-off time, FT = Flight time, JH = Jump Height
\(K_{\text{vert}}\) = Vertical leg-spring stiffness relative to body mass
*Correlation is significant (p < 0.0286), **Correlation is significant (p < 0.007)
#The correlation between FT and JH was not performed as JH was directly derived from FT.
Table 5.4: Inter-correlation matrix between drop jump variables in women. Results are presented as r (95% CI) with statistically significant correlations presented in bold.

<table>
<thead>
<tr>
<th></th>
<th>RSI (m.s(^{-1}))</th>
<th>RSR</th>
<th>CT (s)</th>
<th>T(_{\text{Land}}) (s)</th>
<th>T(_{\text{Push}}) (s)</th>
<th>FT (s)</th>
<th>JH (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSI (m.s(^{-1}))</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RSR</td>
<td>0.91**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0.74 to 0.97)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-0.56</td>
<td>-0.85**</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(-0.84 to -0.04)</td>
<td>(-0.95 to -0.58)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT (s)</td>
<td></td>
<td></td>
<td>0.68*</td>
<td>-0.90**</td>
<td>0.96**</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(-0.89 to -0.23)</td>
<td>(-0.97 to -0.71)</td>
<td>(0.87 to 0.99)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T(_{\text{Land}}) (s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.37</td>
<td>-0.70**</td>
<td>0.95**</td>
<td>0.82**</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(-0.75 to 0.20)</td>
<td>(-0.90 to -0.28)</td>
<td>(0.84 to 0.98)</td>
<td>(0.50 to 0.94)</td>
<td></td>
</tr>
<tr>
<td>T(_{\text{Push}}) (s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.72**</td>
<td>0.37</td>
<td>0.16</td>
<td>-0.01</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(-0.30 to 0.90)</td>
<td>(-0.20 to 0.75)</td>
<td>(-0.40 to 0.64)</td>
<td>(-0.54 to 0.52)</td>
<td>(-0.23 to 0.74)</td>
</tr>
<tr>
<td>FT (s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.71**</td>
<td>0.36</td>
<td>0.18</td>
<td>0.01</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.28 to 0.90)</td>
<td>(-0.21 to 0.75)</td>
<td>(-0.39 to 0.65)</td>
<td>(-0.53 to 0.53)</td>
<td>(-0.09 to 0.84)</td>
</tr>
<tr>
<td>JH (m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.56</td>
<td>0.82**</td>
<td></td>
<td>-0.14</td>
<td>-0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.04 to 0.84)</td>
<td>(0.52 to 0.94)</td>
<td>(-0.98 to -0.78)</td>
<td>(-0.97 to -0.75)</td>
<td>(-0.95 to -0.58)</td>
</tr>
</tbody>
</table>

RSI = Reactive strength index, RSR = Reactive strength ratio, CT = Contact time, T\(_{\text{Land}}\) = Landing time, T\(_{\text{Push}}\) = Push-off time, FT = Flight time, JH = Jump height

K\(_{\text{vert}}\) = Vertical leg-spring stiffness relative to body mass

*Correlation is significant (\(p < 0.0286\)), **Correlation is significant (\(p < 0.007\))

*The correlation between FT and JH was not performed as JH was directly derived from FT.
Table 5.5: Within athlete differences for an exemplar athlete (A) who achieved their highest RSI and RSR in separate trials. Highest RSI and RSR values are marked in bold. Between athlete differences for four athletes who achieved near identical RSI (B and C) and RSR (D and E) values.

<table>
<thead>
<tr>
<th>Athlete</th>
<th>RSI (m.s(^{-1}))</th>
<th>RSR</th>
<th>CT (s)</th>
<th>(T_{\text{Land}}) (s)</th>
<th>(T_{\text{Push}}) (s)</th>
<th>FT (s)</th>
<th>JH (m)</th>
<th>(K_{\text{vert}}) (kN.m(^{-1}).kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Trial 1</td>
<td>2.16</td>
<td>3.61</td>
<td>0.135</td>
<td>0.057</td>
<td>0.078</td>
<td>0.488</td>
<td>0.292</td>
<td>0.866</td>
</tr>
<tr>
<td>A Trial 2</td>
<td><strong>2.18</strong></td>
<td>3.49</td>
<td>0.146</td>
<td>0.060</td>
<td>0.086</td>
<td>0.509</td>
<td>0.318</td>
<td>0.794</td>
</tr>
<tr>
<td>%Δ</td>
<td>-0.6</td>
<td>3.6</td>
<td>-8.1</td>
<td>-5.3</td>
<td>-10.3</td>
<td>-4.3</td>
<td>-8.8</td>
<td>8.3</td>
</tr>
<tr>
<td>Athlete B</td>
<td>2.36</td>
<td>3.64</td>
<td>0.145</td>
<td>0.059</td>
<td>0.086</td>
<td>0.528</td>
<td>0.342</td>
<td>0.834</td>
</tr>
<tr>
<td>Athlete C</td>
<td><strong>2.34</strong></td>
<td>3.28</td>
<td>0.177</td>
<td>0.073</td>
<td>0.104</td>
<td>0.581</td>
<td>0.414</td>
<td>0.596</td>
</tr>
<tr>
<td>%Δ</td>
<td>-0.8</td>
<td>-10.9</td>
<td>18.1</td>
<td>19.2</td>
<td>17.3</td>
<td>9.1</td>
<td>17.4</td>
<td>-40</td>
</tr>
<tr>
<td>Athlete D</td>
<td>1.89</td>
<td><strong>2.79</strong></td>
<td>0.198</td>
<td>0.087</td>
<td>0.111</td>
<td>0.552</td>
<td>0.374</td>
<td>0.399</td>
</tr>
<tr>
<td>Athlete E</td>
<td>1.67</td>
<td><strong>2.81</strong></td>
<td>0.173</td>
<td>0.069</td>
<td>0.104</td>
<td>0.486</td>
<td>0.290</td>
<td>0.682</td>
</tr>
<tr>
<td>%Δ</td>
<td>-12.7</td>
<td>0.8</td>
<td>-14.5</td>
<td>-26.1</td>
<td>-6.7</td>
<td>-13.6</td>
<td>-29</td>
<td>41.5</td>
</tr>
</tbody>
</table>

RSI = Reactive strength index, RSR = Reactive strength ratio, CT = Contact time, \(T_{\text{Land}}\) = Landing time, \(T_{\text{Push}}\) = Push-off time, FT = Flight time, JH = Jump height, \(K_{\text{vert}}\) = Vertical leg-spring stiffness relative to body mass.
5.4 Discussion

5.4.1 Relationship between RSI and RSR

The findings of this study indicate that RSI and RSR had a near perfect positive correlation in male and female athletes. These relationships can best be explained by the common variables, CT and FT, used in the calculation of both measures. The differences between RSI and RSR exist because of the quadratic relationship between FT and JH, i.e. JH is determined directly by the second mathematical equation of linear motion which is a second order polynomial equation. This difference is highlighted in Figure 5.2 which simulates the change in both RSI and RSR as JH increases when CTs are kept constant. RSR will always have a higher value than RSI up until the point at which the absolute value of FT equals the absolute value of JH;
this occurs at an FT of 0.815 s. From this point onwards RSI is higher than RSR. In practical terms this would require an athlete to achieve a JH of 0.815 m which is higher than anything that has been reported within the literature to date. This numerical phenomenon creates a distinction between RSI and RSR and explains why an athlete can achieve higher values for RSI and RSR in separate trials. Consequently, RSI and RSR values should not be compared or used interchangeably. Coaches should consider this when deciding whether to use RSI or RSR as higher JHs will have a greater effect on RSI compared to RSR.

Figure 5.2: Value of RSI (black broken line) and RSR (grey broken line) as jump height increases at constant contact times of (a) 0.200 s, (b) 0.180 s, (c) 0.160 s and (d) 0.140 s. Solid black line denotes point at which RSI and RSR intersect, when jump height = 0.815 m.

5.4.2 Relationship between RSI, RSR and other performance variables
Given that both CT and FT (which was used to directly estimate JH) were used in the calculation of RSI and RSR it was expected that significant correlations would exist between these variables. In the male group, RSI and RSR were significantly related to CT (RSI: very high negative, RSR: very high negative) and JH (RSI: near perfect positive, RSR: very high positive). In the female group, CT was significantly related to RSR only (RSI: high negative, RSR: very high negative) whereas JH was related to RSI only (very high positive). These results suggest that higher RSI scores were typically achieved via a combination of higher
JHs and lower CTs in the males and via higher JHs in females. Similarly, higher RSR values were also typically achieved via a combination of higher JHs and lower CTs in males whereas higher RSR scores were achieved by lower CTs in females. Lowering CT will reduce the time available to develop and apply force and thus generate an impulse. Net jump impulse is determined by the area of the force-time curve during the ground contact phase. The interaction between force and time is important to consider as a decrease in CT with a proportional increase in force will result in FT / JH being maintained which will result in a higher RSI / RSR value. However, if there is not a proportional increase in force then FT / JH will decrease. Whether or not this has a positive or negative impact on RSI / RSR will be dependent on the magnitude of the change in CT and FT / JH i.e. if the positive effect of a reduced CT outweighs the negative effect of a lower FT / JH.

$K_{vert}$ had a significant negative relationship with CT in both male (very large) and female (near perfect) athletes with a significant large positive relationship found with JH in men only. A higher $K_{vert}$ would suggest a greater ability to resist negative displacement of the COM and thus spend less time in the landing phase of a drop jump. This is supported by the near perfect negative relationship found between $K_{vert}$ and $T_{Land}$ in both male and female athletes. This is consistent with the literature on drop jumping as higher levels of $K_{vert}$ have been found in jumps with lower CTs (Arampatzis et al. 2001b; Arampatzis et al. 2001a). The very large relationship between $K_{vert}$ and CT explains why $K_{vert}$ had a very high positive correlation with RSI and RSR in males. Recent research by Kipp et al. (2017) also found a large positive relationship between $K_{vert}$ and RSI using the same box height (0.3 m) as the present investigation. In the female group, a very high correlation was found with RSR only. The lack of a significant relationship between $K_{vert}$ and RSI in females can be explained, by the lack of association between CT and RSI. Although it may be tempting for coaches to use RSI as an indicator of $K_{vert}$, the data from this study illustrates that the strength of the relationship between $K_{vert}$ and RSI will largely depend on the strength of the relationship between CT and RSI.

The differences in correlations between the male and female groups can be explained by differences in individual athlete’s performance strategies (i.e. how an athlete achieves the outcome performance). Theoretically, the maximum number of performances yielding identical RSI / RSR scores depends on the difference between the longest allowable CT and the shortest CT achieved by an athlete in the group tested. In this study, this would be 0.250 s.
– 0.137 s = 0.114 s or 114 performances with distinct CT and JH / FT values. To put this into context, two athletes could achieve an RSI of 2 m.s⁻¹ by jumping with a CT = 0.137 and JH = 0.247 m or CT = 0.250 s and JH = 0.450 m. Examples of this are given in Table 5 where Athlete B and C achieved RSI values of 2.36 m.s⁻¹ and 2.34 m.s⁻¹ respectively. Athlete B had an 18.1% shorter CT and a 17.4% lower JH than Athlete C. This illustrates two alternative performance strategies that require different physical capacities i.e. a greater ability to tolerate a stretch load and thus achieve a shorter contact time and a greater ability to generate an impulse and thus achieve a higher JH. This highlights that an athlete’s specific strengths, in tolerating a stretch load, rapidly developing an impulse or achieving a balance of both, cannot be clearly identified by an RSI or RSR value in isolation. This phenomenon may have affected the relationship between RSI and sprint performance in Chapter 4.

5.4.3 Problems with the calculation of RSI and RSR

There are problems related to the calculation of RSI and RSR measures. To express RSI values as a comparable measure between performances, the numerator in the equation i.e. JH must be expressed over a common denominator i.e. a CT of 1 s. For example, for an athlete with JH = 0.3 m and CT = 0.200 s, to achieve a denominator of 1 s, RSI would be calculated by multiplying both the JH and CT by five, yielding an RSI of 1.5 m.s⁻¹. Consequently, the calculation of RSI assumes that JH would increase in direct proportion to increases in CT. From a theoretical perspective, this assumption ignores one of the fundamental conditions for effective SSC function mentioned previously i.e. a short and fast eccentric phase (Komi and Gollhofer 1997). The longer the CT the lower the benefit provided by mechanisms such as the stretch reflex on the performance of fast SSC movements such as the drop jump (Enoka 2015).

The problem with RSR arises from the fact that JH does not increase in a directly linear proportion to FT. The vertical distance travelled by the COM in 1 ms of flight time is dependent entirely on the magnitude of the COM’s vertical velocity at that time i.e. the greater the velocity the greater the distance travelled. This can result in misleading results when comparing RSRs. For example, two performances with a RSR of 3, representing a 3:1 ratio of FT to CT. One performance is achieved with CT = 0.140 s and the other achieved with a CT = 0.250 s. By calculating the JH based on the FT (calculated by tripling CT) we see that the first performance yielded a RSI of 1.55 m.s⁻¹ whereas the second yielded a RSI of 2.76 m.s⁻¹. (i.e. ~78% greater). The RSI of the second performance would be considered
exceptionally high relative to the present data set and the extant literature, thus illustrating a major problem with RSR.

All of the aforementioned issues can be largely reduced by controlling for CT, therefore, to accurately compare RSI / RSR values, the variability in CT must be reduced so that any difference in RSI / RSR can largely be attributed to differences in JH. This can be accomplished by providing stricter instructions on maximally acceptable contact times or by emphasising the need to get off the ground as quickly as possible. These actions should narrow the range of CTs within a data set and in doing so, should maximise the relative importance of JH. A revised definition of reactive strength should therefore be adopted as: the ability to tolerate a stretch load and subsequently generate an impulse within a specified time.

5.5 Practical Recommendations

Practitioners are urged to consider the findings of this study when assessing RSI and RSR measures in their athletes. Firstly, coaches and clinicians should be aware of the difference between RSI and RSR especially when reading the scientific literature as very few authors have explicitly made the distinction between these two indices. Therefore, it is proposed that researchers use the terminology appropriate to the different calculation methods as outlined in this study i.e. RSI when JH is divided by CT and RSR or flight to contact time ratio when FT is divided by CT, when reactive strength measures are assessed.

Practitioners should also be wary of directly comparing athletes’ RSI or RSR values or using RSI or RSR group normative values as aggregate scores may mask valuable information about individual strategies. Consequently, values should always be presented with the corresponding CTs and JHs or FTs to give greater context to the athlete’s performance. For example, if the reactive strength of a high jump athlete is being assessed, then JH is a critical factor as generating a large impulse at take-off is crucial to success. However, if RSI / RSR improves over time through lower CTs but also lower JHs then this can potentially be considered a negative change. If between-athlete comparisons are desired, coaches are advised to enforce strict testing rules in relation to drop jump contact times in order to avoid reactive strength measures becoming confounded by differences in jumping strategy. This can be accomplished by determining more specific upper and / or lower contact time thresholds where jump trials are not accepted if the contact times fall outside of the pre-
determined thresholds. The determination of upper and / or lower thresholds will depend on the capabilities of the group of athletes being tested, the demands of the specific sport e.g. < 0.200 s for the initial steps of a sprint, or simply whichever criteria yields the most reliable performances which can only be determined through “in-house” testing. Additionally, the height of the box used for the drop jump may need to be reduced if an athlete cannot achieve a contact time lower than the maximum threshold. This could be an indication that the athlete possesses poor levels of relative strength or poor stiffness capabilities.

Although jump mats, photoelectric cells and mobile applications are commonly used to assess drop jump performance measures (CT, JH, RSI, RSR), valuable kinetic data can only be assessed directly using more sophisticated equipment e.g. force platforms, which provide much greater information on an athlete’s physical capacities.

5.6 Conclusions
This study found near perfect and very large correlations between RSI and RSR in male and female sprinters respectively. Although highly related, distinctions in measures do exist and can be explained by the quadratic relationship between FT and JH. The results also demonstrate that the method of assessing reactive strength (RSI versus RSR) may be influenced by the performance strategies adopted i.e. whether an athlete achieves their best reactive strength scores via low CTs, high JHs or a combined approach. Accordingly, drop jump RSI should not be used an indicator of \( K_{\text{vert}} \) as performance strategies that favour higher jump heights over shorter contact times will yield misleading results. Coaches are advised to limit the variability in performance strategies by implementing upper and / or lower CT thresholds to accurately compare performances between individuals or when assessing relationships between reactive strength and other performance abilities, such as sprinting in Chapter 4.
Chapter 6: Resistance Training Practices of Sprint Coaches

This chapter has been accepted for publication in the following journal:
6.1 Introduction

Sprinting is a multidimensional skill with distinct kinetic and kinematic requirements during the acceleration, maximum velocity and deceleration phases (Delecluse et al. 1995; Delecluse 1997). Sprinting requires very large average forces (>2 × body weight) to be produced over very short time periods (~0.080 – ~0.200 s) in addition to the effective application of force in both the vertical and horizontal directions (Weyand et al. 2000; Hunter et al. 2005; Weyand et al. 2010; Morin et al. 2011; Morin et al. 2012). Consequently, various methods are typically employed to enhance sprint performance. These include, free sprint training, resisted and assisted sprint training, implementation of sprint specific technical drills and finally resistance training (RT) which aims to develop a broad range of strength qualities (Delecluse 1997; Bolger et al. 2015; Rumpf et al. 2016; Whelan et al. 2016).

Various studies have assessed the influence of strength qualities i.e. maximum strength, power and reactive strength, on sprint performance in sprint athletes. Maximum strength has frequently been assessed using the back squat and isometric squat with very strong negative correlations reported between back squat relative 1RM and 100 m time (Meckel et al. 1995; Bret et al. 2002) and between isometric squat peak force (PF) and maximum velocity (Young et al. 1995). In contrast Chapter 4 found no significant relationship between PF and relative PF, measured in an isometric mid-thigh pull, and maximum velocity, 10 m split times and mechanical properties during a 40 m sprint. Very large correlations have been reported between power, assessed during jump squats and countermovement jumps, and sprint velocity over 10, 30 and 50 m (Loturco et al. 2015), maximum velocity (Young et al. 1995) and sprint times ranging from 2.5 m to 60 m (Young et al. 1995; Maulder et al. 2006; Loturco et al. 2017).

Research correlating sprint performance and reactive strength, assessed during drop jumping, rebound jumping and hopping, has found conflicting results. Hennessy and Kilty (2001) and Smirniotou et al. (2008) found moderate to very large negative correlations between reactive strength, measured in a drop jump, and sprint times ranging from 10 m to 100 m in female and male sprinters respectively. In contrast, Young et al. (1995), Loturco et al. (2017) and Chapter 4 did not find any significant relationship between reactive strength and sprint times ranging from 2.5 m to 60 m. Furthermore, Nagahara et al. (2014) found a moderate negative relationship between reactive strength, measured in hopping, and 60 m sprint time whereas no relationship was found for rebound jump reactive strength. Chapter 6 highlighted issues
with the use of the reactive strength index (RSI) as an indicator of reactive strength which may explain the conflicting findings within the literature.

Although the number of RT intervention studies on sprint athletes is limited, several studies have reported positive effects on sprint performance using traditional resistance training exercises (Blazevich et al. 2002; Satkunskiene et al. 2009), ballistic exercises (Balsalobre-Fernandez et al. 2013) and plyometric exercises (Satkunskiene et al. 2009; Kamandulis et al. 2012). In traditional resistance training exercises the load is decelerated near the end of range of motion e.g. back squat and step up (Cormie et al. 2011). Conversely, in ballistic exercises the load is accelerated throughout the entire range of motion to the point at which the barbell is released or the athlete leaves the ground e.g. jump squats and high pulls (Cormie et al. 2011). Plyometric exercises are characterised as movements that utilise a rapid stretch shortening cycle action where an eccentric muscle action is coupled with a concentric muscle action (Nicol et al. 2006). Although plyometric exercises are also ballistic in nature they are typically performed with no additional weight and overload is generally achieved by reducing the duration of the stretch shortening cycle (Smith et al. 2011) or by increasing the stretch load (Cormie et al. 2011; Cappa et al. 2013).

Objections to the inclusion of ballistic and traditional exercises in a sprinter’s preparation have arisen from sprint coaches due to the perceived lack of biomechanical specificity, relating to the ground contact times required and the kinetic demands placed on the lower body during sprinting (Bolger et al. 2016; Moir et al. 2018). Bolger et al. (2016) found that expert sprint coaches select a wide range of track and gym based RT exercises for their sprint athletes with a range of explanations offered for the inclusion of each exercise. However, this research focused on the use of back squats, Olympic lifts and their variations in a small sample of coaches (n = 7). Consequently, research on a larger sample of coaches with a wider range of experience is required to provide a more comprehensive overview of the current practices of sprint coaches. Additionally, a more thorough investigation is warranted to determine the primary reasons coaches prescribe RT to their athletes and why they select the exercises they select. This information is needed to inform the development of future coaching educational resources and to direct further research on resistance training for sprint athletes.
Studies, utilising semi structured interviews, have been conducted on small samples (n = 7) of expert sprint coaches to gain insight into their technical knowledge of race phases (Jones et al. 2009), the characteristics of good sprinting technique (Jones et al. 2009, Thompson et al. 2009) and their perceptions of RT (Bolger et al. 2016). In addition to semi structured interviews, surveys have been utilised within the literature. Survey research can effectively gather large amounts of data from greater samples compared to interviews; however, the depth of information gathered may not be as extensive (Kelley et al. 2003). Whelan et al. (2016) conducted a survey on a large sample of sprint coaches (n = 209) with a wide range of experience to ascertain their technical knowledge of sprint drills and their rationale for selecting specific drills. Survey designs have frequently been used to investigate the training practices of S & C coaches in NFL (Ebben and Blackard 2001), hockey (Ebben et al. 2004), baseball (Ebben et al. 2005), basketball (Simenz et al. 2005), rowing (Gee et al. 2011), Rugby union (Jones et al. 2016) and swimming (Crowley et al. 2018). These studies have presented a thorough overview of training practices which can be used to develop educational resources and workshops for coaches in their respective sports.

While most of the above studies assessing RT practices have focused on surveying the strength and conditioning coaches, this paper instead surveys sprint coach responses since sprint coaches tend to be highly involved with the implementation of RT with their sprint athletes (Bolger et al. 2016). Consequently, the aims of this study were to investigate why sprint coaches prescribe RT to their athletes, what exercises they select and what factors are involved with their selection.

6.2 Methods

6.2.1 Experimental Approach to the Problem

This study used an online self-administered questionnaire of sprint coaches registered with Athletics Ireland. There was no leading hypothesis and the questionnaire was designed to answer the two main research questions: what RT exercises are prescribed by sprint coaches to their athletes and why they are prescribed.

6.2.2 Subjects

Forty-one (n = 30 male, n = 11 female) sprint coaches currently coaching in the Republic of Ireland (40), and Northern Ireland (1) were included in this study. The inclusion criteria were: coaches had to be coaching athletes in a sprint event, their athletes had to be currently
performing RT and they had to fully complete the questionnaire. For the purposes of the current study, RT involved weight training and plyometric / jump type training that could be performed in a gym setting only, with resisted sprinting excluded. Ethical approval for this research was provided by the University Research Ethics Review Board. All participants were informed of the benefits and risks of participating and informed consent was completed before undertaking the questionnaire in compliance with the Declaration of Helsinki.

6.2.3 Procedures
The questionnaire was circulated to a database of athletics coaches registered with Athletics Ireland previously used in research assessing sprint coaches (Whelan et al. 2016). An introductory letter accompanied the questionnaire outlining the purpose of the questionnaire, the time commitment required and the confidentiality of information. The questionnaire, “The Resistance Training Practices of Sprint Coaches” was developed using a commercially available online survey generator (Survey Monkey, Inc, San Mateo, CA, USA). The questionnaire consisted of five sections: (1) informed consent, (2) coach background information, (3) coach education and qualifications, (4) coaches’ views on resistance training and (5) exercise selection & preference. As exercise prescription varies throughout the year in any well-structured resistance training programme, the exercise selection & preference section was further divided into three additional sub sections: traditional exercises, ballistic exercises and plyometric / unweighted jump type exercises. In each sub-section a series of resistance training exercises, typically seen in the RT literature, were illustrated similar to previous research (Whelan et al. 2016) and coaches were asked which exercises they prescribed regularly over the course of a year, which two exercises they considered most important and why. Coaches were also given an opportunity to include any other RT exercise or variation that their athletes performed regularly. The questionnaire was pilot tested with an advisory group of four sprint coaches to assess the validity of the instrument for the targeted population. The questionnaire was subsequently revised to improve the clarity and wording of questions. The questionnaire responses were exported to Microsoft Excel for the final analysis.

6.2.4 Statistical Analysis
The responses of the coaches that met the inclusion criteria were considered as raw data. The questionnaire contained both open ended and fixed response questions. Fixed response
questions regarding the coaches’ background information, education, qualifications, RT exercises prescribed and preferred RT exercises were assessed using a frequency analysis. A thematic analysis approach was used to assess open ended questions in order to determine the reasons coaches prescribe RT and their rationale for prioritising certain exercises. This thematic analysis was conducted according to the six stage process outlined by Braun and Clarke (2006) and previously used by studies surveying coaches (Whelan et al. 2016; Crowley et al. 2018). The six stages were as follows: (i) data familiarisation, (ii) generating initial codes, (iii) searching for themes, (iv) reviewing themes, (v) defining and naming themes and (vi) producing the report. Using this approach, overarching clear and identifiable distinct themes, representing the main ideas or patterns emerging from the raw data, were generated for each of the open ended questions. In some instances, coaches’ responses provided sufficient information such that more than one overarching theme could be identified.

6.3 Results

6.3.1 Coach Background Information

A total of 73 sprint coaches responded to the survey request with 41 (56%) coaches meeting the inclusion criteria. Of the 32 excluded coaches, 34.4% did not prescribe RT to their athletes and the remaining 65.6% of coaches did not complete the questionnaire. The included sprint coaches had a mean ± SD coaching experience of 8.4 ± 6.4 years with 43.9%, 36.6% and 19.5% coaches having coached athletes up to international, national and regional levels respectively.

6.3.2 Coach Education & Qualifications

Of the total sample, 87.8% of coaches had a coaching qualification in athletics. Coaching qualifications included Athletics Ireland Level 1 (29.3%), Level 2 (22.0%) and Level 3 or internationally equivalent (36.6%). Level 3 qualifications are comparable to IAAF Level 4. 9.8% of the coaches surveyed held a qualification in strength and conditioning, with 7.3% holding a National Strength and Conditioning Association (NSCA) Certified Strength and Conditioning Specialist (CSCS) accreditation and 2.4% holding a degree in strength and conditioning.
6.3.3 Coaches’ Views on Resistance Training

The coaches were asked to state how important they believed RT was to their athletes for speed development. Coaches reported that RT was somewhat important (2.4%), important (26.8%), and very important (70.7%) with no coach considering RT not important.

The thematic analysis of the coaches’ beliefs on why sprinters should perform RT resulted in six distinct themes outlined in Table 6.1 along with exemplar responses for each theme. The three most prominent themes were: the development of strength (19 coach responses), the development of power (16 coach responses), and the transfer to sprint performance (14 coach responses).
Table 6.1: Coaches’ beliefs about why sprinters should perform RT

<table>
<thead>
<tr>
<th>Rank</th>
<th>Theme</th>
<th>Exemplar Responses</th>
<th>Number of Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Development of strength</td>
<td>“To develop strength for speed.” (Coach #22)**</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“Improves muscular strength.” (Coach #34)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Development of power</td>
<td>“To aid in the development of explosive power.” (Coach #2)</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“Athletes will have faster reacting muscles (more power).” (Coach #26)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Transfer to sprint performance</td>
<td>“Develop power and speed by developing strength in the muscle groups that drive speed.” (Coach #5)**</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“Helps improve stride length by improving strength and power” (Coach #36)**</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>To prepare the body to withstand loads and prevent Injuries</td>
<td>“Prevent injury when athletes train / compete at maximum speeds.” (Coach #1)</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“Resistance to injury.” (Coach #19)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Development of elastic / reactive strength / explosiveness</td>
<td>“To improve muscle elasticity.” (Coach #7)</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“It helps to develop the CNS as well as elastic strength.” (Coach #37)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Overall athlete development</td>
<td>“Athlete weight training is important only as a supplement to what they do on the track.” (Coach #29)</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“It is an integral part of a complete training programme.” (Coach #40)</td>
<td></td>
</tr>
</tbody>
</table>

** Indicates responses that were coded under more than one theme
### 6.3.4 Exercise Selection & Preference

Table 6.2 outlines the sources of information coaches used to aid in RT exercise prescription. The three most widely used sources of information were from coaching courses (78.0%), other coaches (78.0%) and from research articles (70.7%). 91.2% of all coaches used at least three sources of information, 70.7% used at least four and 56.1% used at least five.

<table>
<thead>
<tr>
<th>Source of Information</th>
<th>Proportion of Coaches (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coaching Courses</td>
<td>78.0</td>
</tr>
<tr>
<td>Other Coaches</td>
<td>78.0</td>
</tr>
<tr>
<td>Research Articles</td>
<td>70.7</td>
</tr>
<tr>
<td>Online Sources</td>
<td>61.0</td>
</tr>
<tr>
<td>Previous Experience</td>
<td>56.1</td>
</tr>
<tr>
<td>Coaching Conferences or Seminars</td>
<td>53.7</td>
</tr>
<tr>
<td>Books</td>
<td>53.7</td>
</tr>
<tr>
<td>From the Athletes</td>
<td>24.4</td>
</tr>
</tbody>
</table>

When asked who was responsible for selecting exercises for their athletes 43.9% of the coaches reported that they were solely responsible, 43.9% worked in conjunction with a strength and conditioning coach, 7.3% worked with another sprint coach or coaches, 2.4% left the exercise selection up to another sprint coach, and 2.4% left the exercise selection up to the strength and conditioning coach.

The coaches collectively provided an extensive list of 34 exercises comprised of 14 traditional exercises, 5 ballistic exercises and 15 plyometric / unweighted jump type exercises that their sprint athletes performed regularly. Figure 6.1 illustrates the prescription frequency for each exercise. The hurdle jump was the most widely prescribed exercise with 93% of coaches reporting its use with their athletes. The jump squat was the most widely prescribed ballistic exercise (66% of coaches) whereas the barbell step up was the most widely prescribed traditional exercise (61% of coaches).
Figure 6.1: The prescription frequency of each of the listed exercises. Only exercises with a response frequency >5% are included. Plyometric / unweighted jump type exercises are in black & white, ballistic exercises are in grey and traditional exercises are in black.

Coaches were asked to state which two exercises they considered most important in each RT exercise category. The results are outlined in Table 6.3 with the hurdle jump considered the most important plyometric exercise (68.3% of coaches), the jump squat considered the most important ballistic exercise (61.0% of coaches) and the barbell step up considered the most important traditional exercise (43.9% of coaches).
Table 6.3: The top three exercises considered to be the most important in each RT exercise category.

<table>
<thead>
<tr>
<th>Category</th>
<th>Exercises Reported as most important (% of Coaches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional Exercises</td>
<td>Barbell Step Up (43.9)</td>
</tr>
<tr>
<td></td>
<td>Barbell Lunge (41.5)</td>
</tr>
<tr>
<td></td>
<td>Back Squat (29.3)</td>
</tr>
<tr>
<td></td>
<td>Jump Squats (61.0)</td>
</tr>
<tr>
<td>Ballistic Exercises</td>
<td>Kettlebell Swings (43.9)</td>
</tr>
<tr>
<td></td>
<td>Power Clean (39.0)</td>
</tr>
<tr>
<td>Plyometric / Unweighted Jump</td>
<td>Hurdle Jumps (68.3)</td>
</tr>
<tr>
<td>Type Exercises</td>
<td>Squat Jumps (34.1)</td>
</tr>
<tr>
<td></td>
<td>Ankle Hops (26.8)</td>
</tr>
</tbody>
</table>

The thematic analysis applied to the coaches’ responses on their rationale for choosing their most important exercises resulted in five distinct themes. The themes identified were: performance adaptations, practicality, muscles / muscle groups, exercise characteristics and similarity to sprinting. The response frequency of the five themes and exemplar responses for each theme are outlined in Tables 6.4-6.6 for traditional exercises, ballistic exercises and plyometric / unweighted jump type exercises respectively. The most prominent themes emerging from the data set were muscles / muscle groups for the traditional exercises and performance adaptations for the ballistic and plyometric exercises. When all three exercise types were combined the emerging themes were ranked as follows: 1) performance adaptations (33 responses); 2) practicality (20 responses); 3) muscles / muscle groups (15 responses); 4) exercise characteristics (14 responses) and 5) similarity to sprinting (9 responses).

The responses, grouped under the theme of performance adaptations, were further categorised based on the physical quality targeted for each of the RT exercise types and are given in Table 6.7. Four qualities emerged from the data set; strength, power and reactive strength / explosiveness. Strength (3 responses), power (7 responses) and strength / reactive strength / explosiveness (5 responses each) were the most common physical qualities mentioned for traditional exercises, ballistic exercises and plyometric / unweighted jump type exercises respectively.
Table 6.4: Coaches’ rationales for choosing their most important traditional exercises

<table>
<thead>
<tr>
<th>Rank</th>
<th>Theme</th>
<th>Exemplar Responses</th>
<th>Number of Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Muscles / Muscle Groups</td>
<td>“Hip thrust strengthens the glutes which are the primary hip extensor.” (Coach #9 regarding hip thrusts)</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“One hip dominant and one knee/ hip exercise with a high transfer to sprinting.” (Coach #38 regarding step ups and deadlifts)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Practicality</td>
<td>“Easy to demonstrate and easy to do.” (Coach #7 regarding step ups and split squats)</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“Doesn’t take too much time to get maximum return for input.” (Coach #30 regarding step ups and deadlifts)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Performance Adaptations</td>
<td>“Single leg (dominant) exercises to prevent imbalances.” (Coach #4 regarding step ups and split squats)</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“Max strength from squats benefits all round training” (Coach #10 regarding back squats and lunges)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Similarity to Sprinting</td>
<td>“Resembles the sprinting action the closest.” (Coach #6 regarding step ups and split squats)</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“Stance of one foot in front of the other mimics running best.” (Coach #23 regarding step ups and lunges)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Exercise Characteristics</td>
<td>“More dynamic exercises.” (Coach #15 regarding step ups and lunges)</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“Full range of movement.” (Coach #39 regarding step ups and deadlifts)</td>
<td></td>
</tr>
</tbody>
</table>
Table 6.5: Coaches’ rationales for choosing their most important ballistic exercises

<table>
<thead>
<tr>
<th>Rank</th>
<th>Theme</th>
<th>Exemplar Responses</th>
<th>Number of Responses</th>
</tr>
</thead>
</table>
| 1    | Performance Adaptations       | “These are great exercises for enhancing maximum power output especially in the lower body.” (Coach #27 regarding jump squats and power cleans)  
                            | “Used for time and found increases in dynamic strength.” (Coach #31 regarding jump squats and power cleans) | 10                  |
| 2    | Exercise Characteristics      | “Functional and reactive.” (Coach #1 regarding the jump squat)                     | 6                   |
|      |                               | “High rate of force development. Concentric & eccentric components. Co-ordinated movements.” (Coach #39 regarding the power clean and power snatch) |                     |
| 3    | Practicality                 | “Require less technical proficiency.” (Coach #9 regarding kettle bell swings and the high pull)  
                            | “These exercises are easy to coach and easy for the athletes to learn but still very effective.” (Coach #13 regarding kettle bell swings and jump squats) | 5                   |
| 4    | Muscles / Muscle Groups       | “Engaging main power generating muscles [quads; hamstrings; gastrocnemius.” (Coach #8 regarding kettle bell swings and the power snatch) 
                            | “You are hitting muscle groups that will help improve explosive power.” (Coach #15 regarding jump squats and power cleans)** | 2                   |
| 5    | Similarity to Sprinting      | “The exercise replicates the extension phase of sprinting and hurdling technique.” (Coach #12 regarding the jump squat) | 1                   |

** Indicates responses that were coded under more than one theme
Table 6.6: Coaches’ rationales for choosing their most important plyometric / unweighted jump type exercises

<table>
<thead>
<tr>
<th>Rank</th>
<th>Theme</th>
<th>Exemplar Responses</th>
<th>Number of Responses</th>
</tr>
</thead>
</table>
| 1    | Performance Adaptations      | “Strengthening the legs and helping with ground contact.” (Coach #15 regarding hurdle jumps and squat jumps)  
“To improve reactive/eccentric strength.” (Coach #39 regarding ankle hops and drop to box jumps) | 16                  |
| 2    | Practicality                 | “Minimal Equipment needed. Low risk of injury. Can give a good return for time spent.” (Coach #7 regarding hurdle jumps and ankle hops)  
“They are most convenient and don’t require lots of equipment and they are safe.” (Coach #14 regarding hurdle jumps and box jumps) | 7                   |
| 3    | Exercise Characteristics     | “They require impact absorption & reactive strength in a forward direction.” (Coach #12 regarding hurdle jumps and drop to box jumps)  
“Ankle hops are very short ground contact time.” (Coach #23 regarding ankle hops) | 4                   |
| 4    | Similarity to Sprinting      | “Simple and they replicate shin angles in acceleration and max velocity.” (Coach #10 regarding squat jumps and ankle hops)  
“One exercise with a high transfer to 1st 30 m and one exercise with a high transfer to max speed.” (Coach #38 regarding squat jumps and hurdle jumps) | 3                   |
| 5    | Muscles / Muscle Groups      | “Engaging main power generating muscle groups.” (Coach #8 regarding hurdle jumps and drop to box jumps)  
“Range of muscle groups recruited.” (Coach #19 regarding hurdle jumps and drop jumps) | 2                   |
<table>
<thead>
<tr>
<th>Strength Quality</th>
<th>Strength</th>
<th>Power</th>
<th>Reactive Strength / Explosiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional Exercises</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ballistic Exercises</td>
<td>4</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Plyometric / Unweighted Jump Type Exercises</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>12</strong></td>
<td><strong>11</strong></td>
<td><strong>5</strong></td>
</tr>
</tbody>
</table>

6.4 Discussion
This study sought to conduct a comprehensive survey of sprint coaches’ beliefs and practices regarding RT and the selection of RT exercises. Both the current survey response rate (56%) and total number of coaches surveyed (n = 41) compares well with previous research on the strength and conditioning practices of coaches in a single sport (Response Rate Range: 34% - 84%; Sample size Range: 20 – 43 coaches, (Ebben et al. 2005; Simenz et al. 2005; Jones et al. 2016). However, Whelan et al. (2016), who surveyed sprint coaches regarding their knowledge and use of sprinting drills, had a larger response rate of 74.9% with a final sample of 209 coaches included. Whelan et al. (2016) did not report the mean ± SD coaching experience or the level of athletes the coaches were involved with, so no comparisons could be made with the current study. The coaches surveyed in the present study were of a proportionally higher level, in coaching qualifications, with 58.5% of respondents holding a Level 2 coaching qualification or higher, compared to ~30% in Whelan et al. (2016). Additionally, the high quality of coaches in the current sample is further demonstrated as 19.5% of the coaches surveyed would be considered expert coaches based on the criteria used in previous research on sprint coaches i.e. ≥ 10 years coaching experience, hold the highest coaching qualification available in athletics and had experience coaching international level athletes (Jones et al. 2009; Thompson et al. 2009; Bolger et al. 2016).

The decision to survey sprint coaches rather than strength and conditioning coaches was justified by the results demonstrating that 95.1% of surveyed sprint coaches were directly involved with the selection of RT exercises. Conversely, 46.3% of coaches reported that an S & C coach was involved with the selection of RT exercises. This finding is important given that only 9.8% of sprint coaches surveyed reported having a qualification in strength and
conditioning. Although a coach can develop sufficient knowledge without a formal qualification in strength and conditioning, accreditations, such as the NSCA CSCS, have been reported to increase knowledge of the provision of strength and conditioning programs (Baechle and Earle 1992; Tapley et al. 2014). Ultimately, the decision to undertake a formal qualification in strength and conditioning will depend on factors such as the time / resources available to the coach and whether or not the knowledge acquired from the qualification provides a benefit in athlete performance outcomes.

All coaches surveyed believed RT was, at the very least, somewhat important for speed development with the majority of coaches (70.7%) believing it was very important. This finding is consistent with Bolger et al. (2016) who reported that, in a group of seven expert coaches, RT, performed on the track or in a strength and conditioning facility, was universally used to prepare sprinters for competition. The results outlined in Table 6.1 suggest that the most common themes identified for including RT in a sprinter’s preparation were strength development followed by power development. The transfer of RT to sprint performance was only highlighted by 34.1% of coaches. This suggests that coaches view RT predominantly as a means of developing the athlete’s resistance to injury and overall physical abilities in a broader sense through the enhancement of strength, power and reactive strength which supports previous research (Bolger et al. 2016).

Based on the results in Table 6.2, it is apparent that sprint coaches use a wide variety of sources of information when selecting RT exercises for their athletes. Coaching courses and other coaches were the most commonly stated sources of information (78.0% of coaches). This is supported by the findings of Whelan et al. (2016) which found that sprint coaches primarily select sprinting drills for their athletes based on what other successful coaches and athletes use. Similarly, Bolger et al. (2016) reported that expert level sprint coaches selected RT exercises based on a combination of their own personal experience through trial and error and information gleaned through books and from other high level sprint coaches. The current findings highlight the importance of coaching courses and developing a network of experienced knowledgeable coaches to share information about coaching practices. Additionally, the majority of coaches (70.7%) also reported using research articles for information which demonstrates the evidence based approach coaches take to exercise prescription.
It is not known, however, how well coaches have interpreted the scientific literature available to them. A gap between expert sprint coaches’ technical knowledge of sprint technique and the extant scientific literature on sprinting, largely in the field of biomechanics, has been reported previously (Jones et al. 2009; Thompson et al. 2009). Coaches wishing to derive the greatest benefit from the scientific literature on strength and conditioning will thus require additional education to be able to critically evaluate the research in the context of their own practices. There is also a responsibility on sprint researchers to communicate their work as clearly as possible to bridge the gap between practice and the underpinning science.

The hurdle jump was the most commonly prescribed exercise with 93% of coaches reporting its use. Furthermore, the top four exercises, in frequency of prescription, were all plyometric/unweighted jump type exercises. This demonstrates the important contribution plyometric exercises make to a sprint coach’s exercise repertoire. The use of plyometric exercises is common across many sports including hockey (91.3% of coaches) (Ebben et al. 2004) basketball (100% of coaches) (Simenz et al. 2005), baseball (95.2% of coaches) (Ebben et al. 2005), rugby union (95% of coaches) (Jones et al. 2016), and rowing (50% of coaches) (Gee et al. 2011). Although sprint training is the most effective method of developing speed (Rumpf et al. 2016), plyometric training is often used as a supplementary method of speed development (Ebben et al. 2004; Gee et al. 2011; Jones et al. 2016). This supports their widespread use by coaches in the current study and is consistent with the practices of expert sprint coaches and elite level sprinters (Bolger et al. 2016; Bezodis et al. 2018).

The hurdle jump was considered the most important plyometric exercise by 68.3% of coaches in addition to being the most widely prescribed plyometric exercise. Consistent with this finding, the hurdle jump has been recommended as a suitable preparatory exercise for developing maximum speed (Wild et al. 2011). The hurdle jump typically involves short contact times (~0.180 s), requires high knee and ankle stiffness and involves vertical ground reaction forces and rates of force development higher than those observed in other plyometric exercises e.g. countermovement jumps and drop jumps (Song et al. 2010; Cappa et al. 2013). Like sprinting, hurdle jumps are a fast stretch shortening cycle movement (contact times < 0.250 s) and thus their inclusion as a preparatory exercise for sprinters seems warranted. However, to date, only two intervention studies on sprint athletes have included repeated horizontal jumping exercises over barriers, similar to the hurdle jump, with mixed results (Satkunkiene et al. 2009; Kamandulis et al. 2012). Kamandulis et al. (2012) reported a 1.8%
improvement in 60 m sprint time in male Lithuanian national level sprinters after four weeks of power training; whereas Satkunskiene et al. (2009) reported no significant difference in maximum velocity or step kinematic variables in male sprinters after 8 weeks of power training. Both studies incorporated a variety of exercises, in addition to the hurdle jump, so it is inappropriate to attribute the success, or lack thereof, of the interventions to just one exercise.

Although the barbell step up was the most widely prescribed traditional exercise (61% of coaches) and considered the most important traditional exercise (43.9% of coaches), it is largely absent from the RT intervention literature on sprint athletes whereas the back squat does feature (Blazevich et al. 2002). However, the RT literature is limited, with only three intervention studies completed on sprint athletes using the type of RT exercises examined in the present study. Furthermore, Bolger et al. (2016) found that six out of seven expert sprint coaches reported using the back squat whereas only one of the coaches reported using the step up. However, the extant coaching literature recommends the inclusion of both the step up (Wild et al. 2011; Lockie 2018) and the back squat (Wild et al. 2011; Moir et al. 2018) for a sprinter’s general development. Research on the step up, has found higher levels of rate of force development (RFD) during the concentric phase of the lift relative to the back squat (Fauth et al. 2010). Additionally, the high activation of the primary hip extensors, gluteus maximus and hamstrings, supports its inclusion as a strength training exercise with potential transfer to the acceleration phase (Lockie 2018).

The jump squat was the most commonly prescribed ballistic exercise (66% of coaches) and also considered the most important ballistic exercise (61% of coaches). Consistent with this result, Bolger et al. (2016) reported that the jump squat was the most common squatting variation used by expert sprint coaches. Furthermore, research on high level male 400 m hurdlers found a 1.43% improvement in 30 m time after 10 weeks of jump squat training (Balsalobre-Fernandez et al. 2013). The jump squat emphasises explosive concentric force production and consequently is widely used to assess maximum power (Loturco et al. 2015). Furthermore, the jump squat requires activation of the quadriceps and gluteus maximus, the knee and hip extensors, similar to sprint acceleration (Pandy and Zajac 1991; Dorn et al. 2012). Additionally, similar to the hurdle jump and step up, the jump squat has also been recommended for inclusion in a RT program for the sprinter’s overall preparation (Wild et al. 2011) and as a means of developing power (Moir et al. 2018).
The results of the thematic analysis outlined in Tables 6.4-6.6 demonstrate that sprint coaches select RT exercises primarily based on the perceived performance outcome. Additional factors regarding practical implementation i.e. access to equipment / facilities and the perceived ease that the exercise can be demonstrated / coached, were also key factors in exercise selection. Furthermore, coaches considered the targeted muscle groups to a greater extent when selecting traditional exercises such as the step up and back squat than the ballistic and plyometric exercises. Although similarity to sprinting did emerge as a theme, it was the least prominent of all the themes identified. This indicates that the majority of coaches do not consider RT exercises and their similarity to the sprinting action but rather the general performance outcomes they believe will come as result of their inclusion. In contrast, Whelan et al. (2016) found that, when selecting technical drills for sprinting, sprint coaches believe drills should mimic the sprinting action. This is understandable as the purpose of technical drills is to improve sprint technique whereas the purpose of RT is to enhance an athlete’s physical qualities.

The desired performance adaptations outlined in Table 6.7 combined with the emergent themes for selecting RT indicate that coaches primarily select traditional exercises to strengthen key muscle groups, ballistic exercises to develop power, and plyometric / unweighted jump type exercises to develop reactive strength / explosiveness. This is consistent with data from elite sprinters and sprint coaches where maximum strength is typically prioritised further from the competition period with a greater emphasis placed on plyometric exercises and reactive strength as competition approaches (Bolger et al. 2016; Bezodis et al. 2018).

6.5 Conclusion
This study provides a comprehensive description of the RT practices of sprint coaches. Coaching courses play a vital role in the dissemination of information regarding the selection and implementation of RT exercises; the findings of the current study can therefore be used to develop educational resources to maximise the benefits for sprint coaches. Additionally, sprint coaches can use the data presented to expand their current RT exercise repertoire. Furthermore, coaches and researchers alike can use the results of this survey to further the literature on RT for sprinters to help develop more evidence based coaching practises. The hurdle jump was reported to be the most important plyometric exercise as well as being the most widely prescribed exercise; further study is thus warranted. Consequently, to evaluate
the hurdle jump as a sprint specific exercise, Chapter 7 will investigate the kinematic differences between hurdle jumps and maximum velocity sprinting.
Chapter 7: Kinematic Differences between Maximum Velocity Sprinting and Hurdle Jumping In Male Sprint Athletes
7.1 Introduction

The sprint can typically be divided into an acceleration phase, a maximum velocity phase and a deceleration phase (Ae 1992; Mackala 2007; Schiffer 2009). The maximum velocity phase of a sprint can be identified on a sprinter’s velocity-distance curve as a relatively flat section that typically occurs between 50 and 80 m for elite male sprinters (Volkov and Lapin 1979; Krzyztof 2013; Slawinski et al. 2017). The maximum velocity a sprinter can achieve has been shown to be the strongest correlate of success in the men’s 100 m sprint (Volkov and Lapin 1979; Ryu et al. 2012; Slawinski et al. 2017; Chapter 3). Additionally, maximum velocity has been demonstrated to have a strong negative relationship with performance over shorter distances that are traditionally associated with acceleration ability in team sport players (0-9.1 m and 0-18.3 m) (Clark et al. 2017) and sprinters (0-20 m and 0-30 m) alike (Volkov and Lapin 1979; Chapter 3). Consequently, it is unsurprising that maximal velocity sprinting kinematics and kinetics have been widely assessed, as improvements in an athlete’s maximal velocity can increase their chances of success in sprint events (Mero and Komi 1987; Weyand et al. 2000; Kuiten et al. 2002; Bezd et al. 2008; Weyand et al. 2010). Improvements in maximum velocity are typically associated with higher step rates, longer step lengths or a combination of both (Mero and Komi 1987; Hunter et al. 2004; Bushnell and Hunter 2007; Nagahara and Zushi 2017). Higher maximum velocities can be achieved through greater mass specific, stance averaged vertical forces, particularly in the first half of stance through a greater impact velocity of the swing leg on touchdown, applied during very short stance phases (~ 0.100 s) (Mero et al. 1987; Weyand et al. 2000; Weyand et al. 2010; Clark and Weyand 2014).

Although the primary means of enhancing sprint performance is sprint training itself, sprint coaches commonly employ additional methods such as resistance training to develop their sprint athletes’ strength, power and reactive strength (Bolger et al. 2016; Bezd et al. 2018; Chapter 6). Coaches typically prescribe a range of traditional, ballistic and plyometric exercises such as the step up, loaded squat jump and hurdle jump (Bolger et al. 2016; Chapter 6). Unlike traditional and ballistic exercises, plyometric exercises utilise the stretch shortening cycle (SSC) which involves the coupling of an eccentric contraction with a concentric contraction (Nicol et al. 2006). The ground contact time involved in an exercise determines the type of SSC that takes place with contact times ≤ 0.250 s considered fast SSC exercises and contact time > 0.250 s considered slow SSC exercises (Schmidtbleicher 1992).
The SSC found in every ground contact phase of a sprint, especially during maximal velocity, is considered fast, based on the aforementioned criterion and thus the inclusion of fast SSC plyometric exercises, such as the hurdle jump, in a sprinter’s physical preparation appears logical.

Studies comparing the suitability of plyometric exercises to sprinting have assessed either the similarity of exercises to sprinting (Mero and Komi 1994; Kariyama and Zushi 2016) or the biomechanical differences between movements (Okkonen and Hakkinen 2013; Kariyama and Zushi 2016). Mero and Komi (1994) compared maximum velocity sprinting to maximum bounding, stepping and single leg hopping whereas Kariyama and Zushi (2016) compared maximum velocity sprinting to rebound jumps. Okkonen and Hakkinen (2013) compared the block phase of the sprint start with loaded and unloaded countermovement jumps. Both Mero and Komi (1994) and Okkonen and Hakkinen (2013) argued that significant differences in kinematics (higher magnitude angular velocities) or kinetics (higher magnitude vertical forces) indicated that the plyometric exercises imposed greater demands than those present in sprinting and therefore could be considered effective exercises for sprinting. In contrast, Kariyama and Zushi (2016) concluded that the repeated rebound jump could be considered a sprint specific exercise as there were positive correlations between sprinting and rebound jump kinetic measures.

Hurdle jumps, also referred to as barrier hops and double leg hops in the coaching literature (Radcliffe and Farentinos 2015; Haff and Triplett 2016), have been found to be the most widely prescribed resistance training exercise for sprinters and are also considered the most important plyometric exercise by sprint coaches (Chapter 6). However, interventions carried out on sprint athletes utilising hurdle jumps have reported conflicting results. Satkunskiene et al. (2009) found no significant difference after 8 weeks of power training in step kinematic variables or the maximum velocity achieved by male sprinters over 40 m. In contrast, Kamandulis et al. (2012) found a 1.8% improvement in sprint time over 60 m following four weeks of power training in national male level sprinters. Furthermore, hurdle jumps have been recommended as a suitable preparatory exercise for maximum velocity sprinting and the development of reactive ability although they have yet to be compared to sprinting (Young et al. 2001; Wild et al. 2011; Goodwin 2011). Consequently, a direct comparison between the hurdle jump exercise and maximal velocity sprinting is warranted. Significant kinematic
differences may indicate greater physical demands in the hurdle jump and therefore provide additional support for the suitability of the hurdle jump exercise for the development of maximum velocity sprinting.

Coaches can manipulate the hurdle jump exercise to alter the training stimulus by increasing the number of hurdles, thus increasing the repetitions per set, or increasing the height of the hurdles to increase the intensity (Haff and Triplett 2016). Hurdle heights between 0.3 and 0.9 m high (Chu and Myer 2013) are typically recommended with higher heights ~1 m also reportedly used (Cappa and Behm 2011). Previous biomechanical investigations, assessing the hurdle jump, have focused on ascertaining the effects of changing the height of the hurdles (Cappa and Behm 2011), the type of landing (Cappa and Behm 2013), increasing the preceding drop height (Song et al. 2010), and the effects of fatigue (Viitasalo et al. 1993). Increasing hurdle height has been found to significantly increase ground contact times, reduce peak vertical ground reaction force and reduce rate of force development in Rugby players however there is likely considerable variation between subjects regarding the hurdle height at which these decrements occur (Cappa and Behm 2011). Additionally, researchers have compared the hurdle jump to other plyometric exercises (Aura and Viitasalo 1989, Smith et al. 2011). These studies found that the hurdle jump required higher knee and ankle stiffness, greater vertical ground reaction forces and greater rates of force development compared to drop jumps and countermovement jumps (Cappa and Behm 2011; Cappa and Behm 2013).

The ground contact phase provides the only opportunity for an athlete to apply external forces to develop an impulse and subsequently to increase the velocity of their centre of mass (COM). Consequently, the aim of this study was to assess the lower body stance phase kinematic differences in male sprinters between maximal velocity sprinting and hurdle jumps performed over a range of commonly used and prescribed hurdle heights: 0.60, 0.75 and 0.90 m. It was hypothesised that the hurdle jumps would provide significantly longer contact times, greater peak knee flexion and dorsiflexion angles, greater knee flexion and dorsiflexion angular velocities and would also involve greater negative vertical velocities of the lower leg and the COM on touchdown.
7.2 Methods

7.2.1 Experimental Approach to the Problem

In this investigation, the subjects took part in two days of testing with sprint and hurdle jump performances assessed using a 3D motion analysis system. On the first testing day the ground contact phase kinematics of maximum velocity sprinting were recorded during a 50 m sprint. On the second testing day, the ground contact phase kinematics were recorded during hurdle jumps over three hurdle heights: 0.60 m, 0.75 m and 0.90 m which were performed in a randomised order. The dependent variables ground contact time, ankle, knee and hip peak angular velocities, angles at touchdown and take-off and peak plantar flexion and peak knee flexion angles were assessed during each testing session so that the hurdle jump kinematics could be directly compared with the sprint kinematics.

7.2.2 Subjects

Six competitive male collegiate sprinters (mean ± SD, age: 22 ± 4 years; body height: 1.80 ± 0.05 m; body mass: 75.3 ± 7.4 kg, personal best 60 m: 7.01 ± 0.16, personal best 100 m: 10.91 ± 0.26) agreed to participate in this investigation. Three of the athletes competed regularly at an international level whereas the remaining three athletes competed regularly at a national level. Athletes had 5 ± 3 years of sprint training experience and 3 ± 2 years of plyometric training experience. Ethical approval was provided by the institution’s Research Ethics Committee and written consent forms were completed by all athletes prior to testing in compliance with the Declaration of Helsinki.

7.2.3 Experimental Procedures

Sprint and hurdle jump kinematics data were captured using an eleven (six Eagle and five Hawk) camera MAC system (Motion Analysis Corporation, Santa Rosa, CA, USA) operating at 200 Hz. System calibration was performed statically and dynamically using an L-frame reference object and a 500 mm calibration wand, respectively, to define the laboratory origin and global coordinate system. A mean residual marker position error of less than 0.5 mm was found for all testing sessions.

Thirty-two 12.7 mm retro-reflective spherical markers were attached to each sprinter on the ASIS, PSIS, medial and lateral epicondyle, medial and lateral malleolus, 1st and 5th metatarsal, on the athlete’s own spiked shoes, on both the right and left sides. Marker
clusters, consisting of four markers, were also placed on the right and left thigh and shank. Sprinters wore tight fitting black leggings and tops to facilitate the motion capture process. An initial static calibration trial was performed on each sprinter during each testing session to establish joint centres, segment lengths and to define each segment’s local coordinate system with the x-axis pointing to the right, the y-axis pointing forwards and the z-axis pointing upwards. Once the static trial was complete the medial epicondyle and malleolus on the right and left sides were removed.

7.2.4 Sprint Testing Protocol
Sprinters performed three maximal effort 50 m sprints from a standing start on an indoor sprint track after an individualised competition warm up (~ 30 minutes). At least six minutes of recovery time were provided with additional time permitted if requested. The dimensions of the capture volume for the 3D motion analysis were as follows: 7.5 m x 1.25 m x 2.25 m (length x width x height) and was positioned at the 37.5 – 45 m zone of the 50 m sprint. This sprint distance and capture volume has been widely used in studies assessing maximal velocity sprinting (Bezodis et al. 2008; Bezodis et al. 2011; Nagahara et al. 2014). Furthermore, elite male sprinters (100 m sprint PB: 10.43 ± 0.09 s) typically reach 98.5 ± 0.3% of their maximal velocity at 40 m (Chapter 3) and thus, this capture volume was considered appropriate for the current sample. Sprint times were calculated for each trial using two Racetime 2, dual-beam timing gates (Microgate, Bolzano, Italy) positioned at the beginning and end of the capture volume. The maximum velocity for each trial was therefore calculated as the distance covered (7.5 m) divided by the time taken.

7.2.5 Hurdle Jump Testing Protocol
Sprinters performed three repetitions of hurdle jumps over three heights: 0.60 m, 0.75 m and 0.90 m in an indoor biomechanics laboratory after an individualised plyometric specific warm up (~ 20 minutes). The dimensions of the capture volume were 5 m x 1.5 m x 2.5 m (length x width x height). Four hurdles were evenly spaced apart at a distance of 1 m which was considered suitable for the current athlete’s ability level, as determined through pilot testing, as it allowed the successful completion of the hurdle jump trials with no observable deterioration in technique. The kinematic analysis focused on the ground contact phase of the second landing i.e. the landing of the second hurdle jump, similar to previous investigations on hurdle jumps (Cappa and Behm 2011).
One minute rest was provided after each trial and three minutes provided after each hurdle jump height to mitigate the effects of fatigue (Cappa and Behm 2011). For all hurdle jumps subjects were instructed to clear all hurdles while spending as little time as possible on the ground i.e. minimise contact time (Ruben et al. 2010; Cappa and Behm 2011; Cappa and Behm 2013). The subjects’ arm movement was not restricted so that the hurdle jumps were performed identical to how they would be in training i.e. with a double arm swing (Cappa and Behm 2011; Chu and Myer 2013; Radcliffe and Farentinos 2015; Haff and Triplett 2016).

7.2.6 Data Processing
Marker trajectories were digitised and exported using Cortex Motion Analysis Software (version 6.0; Motion Analysis Corporation, Santa Rosa, CA, USA). For all sprints and hurdle jumps the ground contact phase of the right leg was identified as the first and last peak vertical acceleration of the fifth metatarsal marker which corresponded to touchdown and take-off respectively (Bezodis et al. 2007; Hreljac and Marshall 2000; Nagahara and Zushi 2013; Ettema et al. 2016). Subsequently, contact time was calculated as the time elapsed between touchdown and take-off.

The marker coordinate data were used to construct a seven-segment model consisting of the pelvis, right and left thigh, shank and foot was created using Visual 3D (C-Motion, Rockville, MD, USA). The model was scaled to each sprinter using their height and body mass and their segment lengths recorded during the static trial. The vertical velocity of the model’s COM and the lower leg (right shank plus right foot) at touchdown and take-off were calculated through numerical differentiation of the respective COM positions which were calculated using the inertial proportions of Dempster (Dempster 1955). The difference between the vertical velocity of the COM and the lower leg at touchdown gave an indication of whether the lower leg was actively driven into the ground relative to the COM.

Angle rotation around the x-axis i.e. flexion / extension or dorsiflexion / plantar flexion was calculated for the ankle, foot coordinate system around the shank coordinate system, the knee, shank coordinate system around the thigh coordinate system, and the hip, thigh coordinate system rotation around the pelvis coordinate system. The static standing trial was used as a reference point for all joint angles representing neutral or 0° flexion / extension and
dorsiflexion / plantar flexion similar to previous investigations assessing running, sprinting and hurdle jumps (Stefanyshyn and Nigg 1998; Smith et al. 2011; Van Caekenberghe et al. 2013). Positive angles represented extension / plantar flexion whereas negative angles represented flexion / dorsiflexion relative to the static trial. The angle at touchdown and take-off was retained for the ankle, knee and hip; and the peak flexion / dorsiflexion angle was retained for the ankle and knee. Peak hip flexion was not included as a separate variable as this would be equal to the hip angle at touchdown in the sprint. Joint angular velocities were also calculated. The magnitude of the peak extension angular velocity was retained for the ankle, knee and hip whereas the magnitude of the peak flexion / dorsiflexion angular velocity was retained for the ankle and knee only. Similar to the joint angles, positive values represented extension / plantarflexion and negative values represented flexion / dorsiflexion.

All recorded kinematic data were filtered using a fourth-order Butterworth Low-Pass filter with an optimal cut-off frequency of 12 Hz determined via residual analysis (Winter 2009). Sprint and hurdle jump joint angle time histories and angular velocity time histories were interpolated to 101 data points, representing 100% of the ground contact phase, using a cubic spline (Matlab version 8.6, Mathworks, Natick, MA, USA) for graphical purposes only.

7.2.7 Statistical Analyses
All variables were assumed to be normally distributed as the Shapiro-Wilk’s test was found to have an alpha level > 0.05. Descriptive statistics for all variables were presented as mean ± SD. Due to the limited sample size, differences were calculated only between sprinting and each individual hurdle jump condition. Kinematic differences between sprint and hurdle jumps were assessed using paired samples t-tests. The standardised difference between the group means i.e. Cohen’s dz effect size (ES) and accompanying 95% confidence interval (CI) were used to assess the magnitude of differences between groups. The absolute value of the effect sizes were interpreted as trivial (ES < 0.2), small (0.2 ≤ ES < 0.6), moderate (0.6 ≤ ES < 1.2), large (1.2 ≤ ES < 2) very large (2 ≤ ES < 4) and extremely large (> 4) according to the scale proposed by Hopkins et al. (2009). All statistical analyses were performed using SPSS software (version 24.0, SPSS, Inc., IL, USA).
7.3 Results

7.3.1 Contact Time

The mean ± SD maximum velocities achieved during the sprint were 9.55 ± 0.42 m·s⁻¹. Descriptive statistics for individual and group contact times represented in absolute units and as a percentage (%) of sprint contact times are presented in Tables 7.1 and 7.2 respectively. The mean sprint contact times were significantly shorter than those recorded during the 0.60 m hurdle jumps (mean difference ± SD = -0.072 ± 0.036 s, ES = 2.01; 95% CI: 0.96 to 3.05), the 0.75 m hurdle jumps (mean difference ± SD = -0.084 ± 0.038 s, ES = 2.21; 95% CI: 1.16 to 3.26) and the 0.90 m hurdle jumps (mean difference ± SD = -0.082 ± 0.028 s, ES = 2.97; 95% CI: 1.73 to 4.21). All effect sizes were considered very large. Individual hurdle jump contact times ranged from 133-257% of sprint contact times with group mean contact times 174-186% of sprint contact times.

Table 7.1: Mean ± SD individual and group contact times for the sprint, hurdle jump over 0.60, 0.75 and 0.90 m. Significant differences are presented in bold.

<table>
<thead>
<tr>
<th>Athlete</th>
<th>Sprint</th>
<th>0.60 m Hurdle Jump</th>
<th>0.75 m Hurdle Jump</th>
<th>0.90 m Hurdle Jump</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.100 ± 0.000</td>
<td>0.160 ± 0.018</td>
<td>0.195 ± 0.005</td>
<td>0.178 ± 0.015</td>
</tr>
<tr>
<td>2</td>
<td>0.100 ± 0.000</td>
<td>0.148 ± 0.018</td>
<td>0.143 ± 0.003</td>
<td>0.142 ± 0.008</td>
</tr>
<tr>
<td>3</td>
<td>0.100 ± 0.005</td>
<td>0.162 ± 0.003</td>
<td>0.178 ± 0.013</td>
<td>0.217 ± 0.010</td>
</tr>
<tr>
<td>4</td>
<td>0.105 ± 0.009</td>
<td>0.140 ± 0.013</td>
<td>0.153 ± 0.028</td>
<td>0.182 ± 0.016</td>
</tr>
<tr>
<td>5</td>
<td>0.093 ± 0.003</td>
<td>0.227 ± 0.033</td>
<td>0.240 ± 0.035</td>
<td>NA</td>
</tr>
<tr>
<td>6</td>
<td>0.092 ± 0.003</td>
<td>0.182 ± 0.008</td>
<td>0.182 ± 0.003</td>
<td>0.187 ± 0.010</td>
</tr>
<tr>
<td>Group</td>
<td>0.098 ± 0.005</td>
<td><strong>0.170 ± 0.031</strong></td>
<td><strong>0.182 ± 0.034</strong></td>
<td><strong>0.181 ± 0.027</strong></td>
</tr>
</tbody>
</table>

Table 7.2: Individual and group hurdle jump mean contact times represented as a percentage (%) of sprint contact times.

<table>
<thead>
<tr>
<th>Athlete</th>
<th>Sprint</th>
<th>0.60 m Hurdle Jump</th>
<th>0.75 m Hurdle Jump</th>
<th>0.90 m Hurdle Jump</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>160</td>
<td>195</td>
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<td>NA</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>198</td>
<td>198</td>
<td>204</td>
</tr>
<tr>
<td>Group</td>
<td>100%</td>
<td>174 ± 40%</td>
<td>186 ± 42%</td>
<td>183 ± 29%</td>
</tr>
</tbody>
</table>

7.3.2 COM Vertical Velocity at Touchdown and Take-Off

Descriptive statistics for the mean COM vertical velocity at touchdown and take-off are shown in Table 7.3. Significantly lower vertical velocities of the COM at touchdown were found in the sprint compared to the 0.60 m hurdle jump (Mean difference ± SD = 1.98 ± 0.26
118 m·s$^{-1}$, ES = 7.76: extremely large effect; 95% CI: 6.71 to 8.81, $p < 0.001$), the 0.75 m hurdle jump (Mean difference ± SD = 2.23 ± 0.25 m·s$^{-1}$, ES = 8.97: extremely large effect; 95% CI: 7.92 to 10.02, $p < 0.001$) and the 0.90 m hurdle jump (Mean difference ± SD = 2.18 ± 0.15 m·s$^{-1}$, ES = 14.91: extremely large effect; 95% CI: 13.67 to 16.15, $p < 0.001$).

Significantly lower vertical velocities of the COM at take-off were found in the sprint compared to the 0.60 m hurdle jump (Mean difference ± SD = -1.72 ± 0.22 m·s$^{-1}$, ES = 11.50: extremely large effect; 95% CI: 4.63 to 18.10, $p < 0.001$), the 0.75 m hurdle jump (Mean difference ± SD = -1.98 ± 0.22 m·s$^{-1}$, ES = 9.20: extremely large effect; 95% CI: 3.68 to 14.78, $p < 0.001$) and the 0.90 m hurdle jump (Mean difference ± SD = -2.06 ± 0.29 m·s$^{-1}$, ES = 7.03: extremely large effect; 95% CI: 2.35 to 11.81, $p < 0.001$).

### 7.3.3 Lower Leg Vertical Velocity at Touchdown

Significantly lower vertical velocities of the lower leg at touchdown were found in the sprint compared to the 0.60 m hurdle jump (Mean difference ± SD = 0.46 ± 0.43 m·s$^{-1}$, ES = 1.06: moderate effect; 95% CI: 0.01 to 2.11, $p = 0.048$), the 0.75 m hurdle jump (Mean difference ± SD = 0.59 ± 0.26 m·s$^{-1}$, ES = 2.23: very large effect; 95% CI: 1.18 to 3.28, $p = 0.003$) and the 0.90 m hurdle jump (Mean difference ± SD = 0.65 ± 0.21 m·s$^{-1}$, ES = 3.10: very large effect; 95% CI: 1.86 to 4.34, $p = 0.002$).

### 7.3.4 COM Vertical Velocity versus Lower Leg Vertical Velocity at Touchdown

For all conditions the vertical velocity of the COM was significantly different from the vertical velocity of the lower leg at touchdown. In the sprint condition the vertical velocity of the COM was significantly lower (ES = 5.53: extremely large effect; 95% CI: 2.14 to 8.94, $p < 0.001$). The vertical velocity of the COM was significantly higher than the lower leg vertical velocity for the 0.60 m hurdle jump (ES = 1.75: large effect; 95% CI: 0.40 to 3.04, $p = 0.008$), the 0.75 m hurdle jump (ES = 4.58: extremely large effect; 95% CI: 1.73 to 7.43, $p < 0.001$) and the 0.90 hurdle jump (ES = 1.57: large effect; 95% CI: 0.18 to 2.91, $p = 0.024$).
Table 7.3: Mean ± SD velocities for the centre of mass (COM) and lower leg at touchdown for the sprint, hurdle jump over 0.60, 0.75 and 0.90 m. Significant differences are presented in bold.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sprint</th>
<th>0.60 m Hurdle Jump</th>
<th>0.75 m Hurdle Jump</th>
<th>0.90 m Hurdle Jump</th>
</tr>
</thead>
<tbody>
<tr>
<td>COM Vertical Velocity at Touchdown (m·s⁻¹)</td>
<td>-0.68 ± 0.14</td>
<td>-2.66 ± 0.25*</td>
<td>-2.91 ± 0.20*</td>
<td>-2.89 ± 0.22*</td>
</tr>
<tr>
<td>COM Vertical Velocity at Take-off (m·s⁻¹)</td>
<td>0.70 ± 0.20</td>
<td>2.42 ± 0.28*</td>
<td>2.68 ± 0.24*</td>
<td>2.72 ± 0.24*</td>
</tr>
<tr>
<td>Lower Leg Vertical Velocity at Touchdown</td>
<td>-1.99 ± 0.30</td>
<td>-2.45 ± 0.27*</td>
<td>-2.58 ± 0.14*</td>
<td>-2.60 ± 0.33*</td>
</tr>
<tr>
<td>Mean Difference in Vertical Velocity at Touchdown of COM minus Lower Leg (m·s⁻¹)</td>
<td>1.31 ± 0.24*</td>
<td>-0.22 ± 0.12*</td>
<td>-0.33 ± 0.07*</td>
<td>-0.29 ± 0.18*</td>
</tr>
</tbody>
</table>

* Significantly different from Sprint p < 0.05
* COM vertical velocity significantly different from lower leg vertical velocity p < 0.05

Descriptive statistics for the mean ankle, knee and hip angles and angular velocities are shown in Table 7.4. Mean ensemble curves of the ankle, knee and hip angles and ankle, knee and hip angular velocities during sprinting and each hurdle jump height are given in Figures 7.1 and 7.2 respectively.

7.3.5 Ankle Angles
No significant differences were found between the sprint and hurdle jumps for the ankle angle at touchdown. A significantly greater (large effect size) ankle angle at take-off was found in the sprint compared to the 0.75 m hurdle jump only (Mean difference ± SD = 10.4 ± 8.5°, ES = 1.22; 95% CI: 0.17 to 2.27, p = 0.03). Significantly lower peak dorsiflexion angles were found in the sprint compared to the 0.60 m hurdle jump (Mean difference ± SD = 19.6 ± 13.2°, ES = 1.49: large effect; 95% CI: 0.44 to 2.53, p = 0.015), the 0.75 m hurdle jump (Mean difference ± SD = 24.9 ± 7.3°, ES = 3.40: very large effect; 95% CI: 2.35 to 4.45, p < 0.001) and the 0.90 m hurdle jump (Mean difference ± SD = 24.5 ± 12.7°, ES = 1.94: large effect; 95% CI: 0.69 to 3.18, p = 0.012).

7.3.6 Knee Angles
No significant differences were found between the sprint and hurdle jumps for any of the knee angles (p > 0.05).

7.3.7 Hip Angles
Significantly lower hip angles at touchdown were found in the sprint compared to the 0.60 m hurdle jump (Mean difference ± SD = 10.1 ± 7.2°, ES = 1.40: large effect; 95% CI: 0.35 to
2.45, p = 0.19), the 0.75 m hurdle jump (Mean difference ± SD = 9.7 ± 8.5° , ES = 1.14: moderate effect; 95% CI: 0.09 to 2.19, p = 0.38) and the 0.90 m hurdle jump (Mean difference ± SD = 10.4 ± 7.8°, ES = 1.34: large effect; 95% CI: 0.10 to 2.58, p = 0.040). Significantly greater hip angles at take-off were found in the sprint compared to the 0.60 m hurdle jump (Mean difference ± SD = -19.5 ± 6.3° , ES = 3.08: very large effect; 95% CI: 2.03 to 4.13, p = 0.001), the 0.75 m hurdle jump (Mean difference ± SD = -18.9 ± 6.5°, ES = 2.88: very large effect; 95% CI: 1.83 to 3.93, p = 0.001) and the 0.90 m hurdle jump (Mean difference ± SD = -21.0 ± 4.3°, ES = 4.90: extremely large effect; 95% CI: 3.66 to 6.14, p < 0.001).

7.3.8 Ankle Angular Velocities
Significantly lower peak dorsiflexion angular velocities were found in the sprint compared to the 0.60 m hurdle jump (Mean difference ± SD = -5.20 ± 3.45 rad·s⁻¹, ES = 1.51: large effect; 95% CI: 0.27 to 2.69, p = 0.014), the 0.75 m hurdle jump (Mean difference ± SD = -6.18 ± 3.70 rad·s⁻¹, ES = 1.66: large effect; 95% CI: 0.36 to 2.92, p = 0.010) and the 0.90 m hurdle jump (Mean difference ± SD = -5.66 ± 2.67 rad·s⁻¹, ES = 2.12: very large effect; 95% CI: 0.44 to 3.76, p = 0.009).

Significantly greater peak plantar flexion angular velocities were found in the sprint compared to the 0.60 m hurdle jump (Mean difference ± SD = 3.70 ± 1.37 rad·s⁻¹, ES = 2.71: very large effect; 95% CI: 0.88 to 4.50, p = 0.001), the 0.75 m hurdle jump (Mean difference ± SD = 2.51 ± 1.31 rad·s⁻¹, ES = 1.92: large effect; 95% CI: 0.49 to 3.29, p = 0.005) and the 0.90 m hurdle jump (Mean difference ± SD = 2.20 ± 1.08 rad·s⁻¹, ES = 2.04: very large effect; 95% CI: 0.40 to 3.63, p = 0.010).

7.3.9 Knee Angular Velocities
No significant differences were found between the sprint and hurdle jumps for any of the knee angular velocities (p > 0.05).

7.3.10 Hip Angular Velocities
Significantly higher peak extension angular velocities were found in the sprint compared to the 0.60 m hurdle jump (Mean difference ± SD = 6.67 ± 1.98 rad·s⁻¹, ES = 3.37: very large effect; 95% CI: 1.19 to 5.53, p < 0.001), the 0.75 m hurdle jump (Mean difference ± SD =
6.09 ± 2.55 rad·s\(^{-1}\), ES = 2.38: very large effect; 95% CI: 0.73 to 4.00, p = 0.002) and the 0.90 m hurdle jump (Mean difference ± SD = 7.03 ± 1.53 rad·s\(^{-1}\), ES = 4.75: extremely large effect; 95% CI: 1.50 to 8.03, p < 0.001).

Table 7.4: Mean ± SD ankle, knee and hip angles and angular velocities for the sprint, hurdle jump over 0.60, 0.75 and 0.90 m. Significant differences are presented in bold.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sprint</th>
<th>0.60 m Hurdle Jump</th>
<th>0.75 m Hurdle Jump</th>
<th>0.90 m Hurdle Jump</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ankle</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angle at Touch Down (°)</td>
<td>9.1 ± 7.1</td>
<td>12.1 ± 10.7</td>
<td>7.0 ± 11.5</td>
<td>4.0 ± 5.0</td>
</tr>
<tr>
<td>Angle at Take-Off (°)</td>
<td>27.9 ± 6.4</td>
<td>18.5 ± 6.7</td>
<td>17.6 ± 4.3°</td>
<td>18.1 ± 8.4</td>
</tr>
<tr>
<td>Peak Dorsiflexion Angle (°)</td>
<td>-19.3 ± 4.8</td>
<td>-38.9 ± 9.1°</td>
<td>-44.2 ± 5.6°</td>
<td>-43.8 ± 9.5°</td>
</tr>
<tr>
<td>Peak Dorsiflexion Angular Velocity (rad·s(^{-1}))</td>
<td>16.43 ± 1.43</td>
<td>21.62 ± 3.86°</td>
<td>22.59 ± 3.66°</td>
<td>21.90 ± 2.96°</td>
</tr>
<tr>
<td>Peak Plantar Flexion Angular Velocity (rad·s(^{-1}))</td>
<td>22.42 ± 0.94</td>
<td>18.72 ± 2.01°</td>
<td>19.91 ± 1.63°</td>
<td>20.07 ± 1.83°</td>
</tr>
<tr>
<td><strong>Knee</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angle at Touch Down (°)</td>
<td>-30.5 ± 7.3</td>
<td>-26.5 ± 9.2</td>
<td>-30.3 ± 7.1</td>
<td>-31.3 ± 8.7</td>
</tr>
<tr>
<td>Angle at Take-Off (°)</td>
<td>-22.4 ± 9.1</td>
<td>-16.5 ± 10.1</td>
<td>-15.8 ± 7.0</td>
<td>-12.0 ± 7.4</td>
</tr>
<tr>
<td>Peak Flexion Angle (°)</td>
<td>-41.5 ± 7.8</td>
<td>-48.9 ± 15.5</td>
<td>-56.6 ± 17.4</td>
<td>-55.1 ± 8.1</td>
</tr>
<tr>
<td>Peak Flexion Angular Velocity (rad·s(^{-1}))</td>
<td>6.08 ± 3.07</td>
<td>8.53 ± 2.95</td>
<td>9.01 ± 2.36</td>
<td>9.72 ± 2.63</td>
</tr>
<tr>
<td>Peak Extension Angular Velocity (rad·s(^{-1}))</td>
<td>8.50 ± 4.03</td>
<td>9.81 ± 2.14</td>
<td>11.18 ± 2.67</td>
<td>11.80 ± 3.29</td>
</tr>
<tr>
<td><strong>Hip</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angle at Touch Down (°)</td>
<td>27.7 ± 5.5</td>
<td>17.5 ± 3.5°</td>
<td>18.0 ± 7.4°</td>
<td>17.0 ± 7.1°</td>
</tr>
<tr>
<td>Angle at Take-Off (°)</td>
<td>-18.2 ± 8.2</td>
<td>1.3 ± 3.1°</td>
<td>0.7 ± 2.4°</td>
<td>0.6 ± 4.2°</td>
</tr>
<tr>
<td>Peak Extension Angular Velocity (rad·s(^{-1}))</td>
<td>10.75 ± 1.39</td>
<td>4.08 ± 0.76°</td>
<td>4.67 ± 1.50°</td>
<td>4.08 ± 0.76°</td>
</tr>
</tbody>
</table>

* Significantly different from Sprint p < 0.05
Figure 7.1: Mean ensemble of the ankle (Top), knee (Middle) and hip (Bottom) angle during sprinting (solid black line), 0.60 m hurdle jump (broken grey line), 0.75 m hurdle jump (solid grey line) and 0.90 m hurdle jump (broken black line). SD curves omitted for graphical purposes.
Figure 7.2: Mean ensemble of the ankle (Top), knee (Middle) and hip (Bottom) angular velocity during sprinting (solid black line), 0.60 m hurdle jump (broken grey line), 0.75 m hurdle jump (solid grey line) and 0.90 m hurdle jump (broken black line). SD curves omitted for graphical purposes.
7.4 Discussion

The aim of this study was to assess the kinematic differences between maximal velocity sprinting and hurdle jumps performed over 0.60, 0.75 and 0.90 m. The contact times found for maximal velocity sprinting (0.098 s) and hurdle jumps (0.170 – 0.182 s) are consistent with the extant literature (Bushnell and Hunter 2007; Weyand et al. 2010; Cappa and Behm 2011; Cappa and Behm 2013). The hurdle jump contact times were significantly (74-86%) longer than the sprint contact times. Shorter contact times in maximal velocity sprinting were expected and can be explained by several factors. In maximal velocity sprinting, the athletes’ COM will have a much greater horizontal velocity at touchdown and thus their COM will cover the stance distance i.e. the horizontal distance travelled by the COM from touchdown to take-off, quicker (Goodwin 2011). Additionally, a higher negative vertical velocity on touchdown, as found in the current investigation in the hurdles jumps compared to maximal velocity sprinting, will require more time spent applying force to reverse the vertical velocity of the centre of mass and subsequently develop a net positive vertical impulse sufficient to clear the height of the succeeding hurdle.

The contact times displayed in Tables 7.1 and 7.2 demonstrate considerable variation between athletes, with some athletes achieving and maintaining short contact times e.g. athlete 2 (Range: 0.142-0.148 s), whereas other athletes achieved contact longer times and were unable to maintain them e.g. athlete 3 (Range: 0.162-0.217 s). These disparities are potentially due to differences in mean braking forces, vertical stiffness, knee joint stiffness or ankle joint stiffness which have been shown to be related to contact time (Arampatzis et al. 2001a; Charalambous et al. 2012; Douglas et al. 2018). Additionally, different athlete performance strategies may account for some of the observed variation. Athletes can clear a hurdle by raising their COM, achieved by developing greater vertical impulses and thus higher vertical take-off velocities, raising their feet closer to their COM through greater hip flexion, or a combination of both. Although hip mobility is a desirable quality in track sprinters, the purpose of the hurdle jump, as a preparatory exercise for maximal velocity sprinting, is to develop an athlete’s knee and ankle stiffness and the ability to rapidly develop force over short contact times (Goodwin 2011; Wild et al. 2011). Coaches should therefore monitor the contact times and performance strategies their athletes utilise to clear hurdles of varying height. If the contact times are considered excessively long then lower hurdles may be required as contact times > 0.250 s are indicative of a slow SSC movement.
The vertical velocity of the COM during maximal velocity sprinting (-0.68 ± 0.14 m·s⁻¹) is consistent with previously reported values (Mero and Komi 1986; McGowan et al. 2012). Similarly, the mean values for the lower leg vertical velocity at touchdown (-1.99 ± 0.30 m·s⁻¹) are consistent with those recorded previously during maximal velocity sprinting (Mero and Komi 1987). The lower leg vertical velocity was significantly greater than the vertical velocity of the COM at touchdown during the sprint (extremely large effect). This difference can be explained by the impact-limb deceleration mechanism whereby an athlete drives their swing leg into the ground resulting in a greater negative vertical velocity of the foot and shank at touchdown compared to the rest of the body (Clark and Weyand 2014). In the hurdle jumps, however, the opposite result was observed as a significantly lower negative velocity of the swing leg was found compared to the vertical velocity of the COM (large to extremely large effects). This result can be explained by the technique adopted by athletes when clearing a hurdle. Athletes typically flex their hips in the air until their thighs are approximately parallel to the ground in order to clear the hurdle. Upon hurdle clearance, they subsequently extend their hips to adopt a position as close to neutral as possible i.e. thighs perpendicular to the ground, until the point of landing. This action would result in an increased vertical velocity of the pelvis and the right and left thighs, which all contribute to a higher absolute COM landing velocity relative to the lower leg.

The mean ensemble of the ankle angle and angular velocity in the sprint and hurdle jump conditions, shown in Figures 7.1 and 7.2 respectively, all follow a similar trend. Consistent with previous work, on touchdown, the ankle progressively undergoes dorsiflexion until peak dorsiflexion is achieved before mid-ground contact (45% of ground contact phase) and then undergoes plantar flexion until take-off (Mann and Hagy 1980; Stefanyshyn and Nigg 1998; Bezodis et al. 2008; Smith et al. 2011). Significant differences were found in the peak dorsiflexion angle with all hurdle jump conditions displaying significantly greater dorsiflexion than maximal velocity sprinting which suggests that the shank travels further in front of the foot segment during hurdle jumps. Furthermore, the peak dorsiflexion angular velocity was significantly higher in all three hurdle jump conditions compared to the sprint whereas the peak plantar flexion angular velocity was significantly higher in the sprint.

The mean ensemble of the knee angle and angular velocity in sprinting and the hurdle jump conditions, illustrated in Figure 1 and 2 respectively, all follow a similar trend. Consistent
with previous research, on touchdown, the knee progressively undergoes flexion until peak knee flexion is achieved around mid-ground contact (45-50% of ground contact phase) (Mero et al. 1987; Bezodis et al. 2008; Smith et al. 2011; Miller et al. 2012). This is subsequently followed by extension of the knee until the point of take-off. There were no significant differences in peak flexion and extension angles and angular velocities. Greater peak knee flexion and peak flexion angular velocity, relative to the sprint, was expected in the hurdle jump conditions. Although moderate effects were found (ES Range: 0.61 to 1.10), these were not statistically significant and this is possibly due to a lack of statistical power due to the small sample size. Future work is therefore warranted to confirm this.

The mean ensemble of the hip angle and hip angular velocity in the hurdle jump conditions, illustrated in Figures 7.1 and 7.2 respectively, all follow a similar trend. After landing, the hip angle remains relatively constant, in the hurdle jumps, until just before mid-ground contact (40-45% of ground contact phase) and then undergoes extension until the point of take-off which is consistent with previous work (Smith et al. 2011). Whereas in sprinting the hip extended progressively from the instant of touchdown until the point of take-off consistent with previous work (Bezodis et al. 2008). The hip angles in maximal velocity sprinting were significantly different from the hurdle jump conditions with greater hip angles at touchdown and lower hip angles at take-off. Additionally, the peak hip extension angular velocity was significantly greater in the sprint compared to the hurdle jumps. This was expected as, during the stance phase of sprinting, the hip is in a flexed position on touchdown as the COM is positioned behind the stance foot and then the hip extends throughout the stance phase as the COM is projected forward and ahead of the foot (Mann and Hagy 1980; Bushnell and Hunter 2007).

The hurdle jump conditions had significantly greater negative velocities of the COM and lower leg at touchdown compared to the sprint (moderate to extremely large effects). Both sets of differences can likely be explained by a higher vertical position of the COM in the hurdle jumps which is required to clear the height of the hurdle. A higher COM would result in greater time spent falling and thus greater time accelerating downwards due to gravity. Conversely, in the sprint, the athlete requires a vertical impulse to generate sufficient aerial time to reposition their limbs for the subsequent touchdown on the contralateral side (Weyand et al. 2000).
Maximal velocity sprinting is the most appropriate training stimulus to improve maximal velocity sprinting (Rumpf et al. 2016). It is unlikely that any training exercise can closely mimic the kinematic demands of maximal velocity sprinting i.e. contact times of ~ 0.100 s, high ankle, knee and hip extension velocities. The hurdle jump contact times of 0.170-0.180 s are similar to those found in the first two steps of a sprint, only with much lower contact times reported for every subsequent step (Atwater 1982; Salo et al. 2005; Debaere et al. 2013b; Manzer et al. 2016). However, due to the greater negative velocity of the COM and lower leg on touchdown, hurdle jumps, performed over a variety of heights, provide a greater physical demand than that encountered during sprinting as the athlete must reverse their velocity as quickly as possible and develop impulses sufficient to clear the subsequent hurdle. This overload may elicit improvements in maximum velocity sprint performance through enhanced reactive strength i.e. the ability to tolerate a stretch load and subsequently generate an impulse within a specified time (Chapter 5). Furthermore, the hurdle jumps required greater peak dorsiflexion angular velocities and similar knee flexion and extension angular velocity suggesting that it is an appropriate exercise for the ankle and knee joints. Thus, the popularity of the hurdle jump exercise among sprint coaches (Chapter 6) and its inclusion as a preparatory exercise for maximal velocity appears warranted.

7.5 Practical Applications
Hurdle jumps performed over 0.60, 0.75 and 0.90 m have significantly longer contact times, greater peak dorsiflexion angles, greater peak dorsiflexion angular velocities and greater touchdown velocities of both the COM and the lower leg compared to maximal velocity sprinting. The use of a range of hurdle heights is recommended in training as long as an athlete can keep their contact times relatively short and consistent. A large increase in contact times, as a result of increasing the hurdle height, may indicate that the athlete is not conditioned sufficiently to cope with the greater landing velocities. Consequently, careful observation of an athlete’s contact times is recommended. Future work should assess the kinematic and kinetic differences between a range of hurdle heights on a larger sample of sprinters to make more informed decisions regarding individual hurdle height prescription.
Chapter 8: Thesis Conclusions and Implications
8.1 Key Findings, Recommendations and Common Themes

The current programme of research aimed to investigate the importance of 100 m sprint race variables to overall sprint time, advance the understanding of the role of maximum strength and reactive strength in sprint performance and to examine the prescription of resistance training exercises and their suitability for sprint athletes. The key findings of each chapter are described:

Chapter 3 found that four split times: 0-20, 20-40, 40-60 and 60-80 m, measured during a 100 m sprint can be used to accurately model velocity-time and velocity-distance curves in elite male sprinters. Previous studies that have modelled velocity-time and velocity-distance curves have used 3-5 split times but only for distances ≤ 40 m. Chapter 3 demonstrated the importance of maximum velocity not only to 100 m sprint time but also to the acceleration phase as greater maximum velocities were associated with faster sprint times. The estimated acceleration time constant, \( \tau \), was an excellent indicator of a sprinter’s relative acceleration ability with lower \( \tau \) values associated with a greater ability to reach a higher percentage of maximum velocity earlier in the sprint. The modelling approach described in Chapter 3 can provide the coach with valuable race information to evaluate the athlete’s performance capacities i.e. acceleration, maximum velocity and speed endurance which can subsequently be used to further inform training.

Chapter 4 found that reactive strength, measured using the reactive strength index, was not significantly correlated to maximum velocity in a 40 m sprint, 10 m split times or sprint mechanical properties in male and female sprinters. Furthermore, maximum strength assessed during an isometric mid-thigh pull was also not significantly related to sprint performance, although a significantly positive relationship was found between maximum strength and peak horizontal power in men only. Additionally, greater levels of strength were not required to achieve high levels of reactive strength. Although the variables assessed in the isometric mid-thigh pull and the drop jump tests all yielded excellent reliability (ICCs ≥0.87, CV%≤4.9%), their inclusion in the monitoring of sprint athletes is not supported. Finally, coaches and researchers are advised to use split times in addition to outcome measures when investigating correlations with sprint performance as sprinting is a multidimensional skill that requires a wide range of physical and technical demands.
Chapter 5 found that two methods of assessing reactive strength: the reactive strength index and the reactive strength ratio, are highly correlated but several differences exist that are of concern to coaches. The reactive strength ratio is influenced to a much greater extent by an athlete’s ground contact time than the reactive strength index. This suggests that athletes with performance strategies favouring short contact times will be at an advantage compared to athletes with performance strategies favouring higher jump heights. Controlling for differences in performance strategy, through the implementation of contact time thresholds, is required for valid assessments of reactive strength. Additionally, although vertical leg spring stiffness is highly correlated to ground contact time, no significant correlation was found with reactive strength index. Thus, reactive strength index should not be used as an indicator of vertical leg spring stiffness.

Chapter 6 found that sprint coaches prescribe resistance training to develop strength and power which they believe will transfer to their athlete’s sprint performance. Coaches prescribed a range of traditional, ballistic and plyometric exercises with the hurdle jump found to be the most widely prescribed exercise (93% of coaches surveyed). The three most prominent reasons were for coaches to select exercises were: 1) performance adaptations; 2) practicality; 3) the targeting of muscles / muscle groups. Coaches prioritised exercises that specifically developed strength, power and / or reactive strength. Coaches primarily derive their information regarding resistance training from coaching courses and from other coaches. Although coaches are advised to engage in evidence based exercise prescription the research on resistance training exercises for sprinters is sparse. Additionally, it is not known how well coaches have interpreted the scientific literature that is available to them. The findings of Chapter 6 can therefore be used in the development of educational resources for sprint coaches who wish to prescribe resistance training and to further the literature on resistance training for sprinters.

Chapter 7 found that hurdle jumps performed over heights of 0.60, 0.75 and 0.90 m had significantly longer contact times (74-86%) than those observed during maximum velocity sprinting. Additionally, hurdle jumps had significantly greater peak dorsiflexion angles, lower peak hip extension angular velocities, greater peak dorsiflexion angular velocities, similar peak knee extension and flexion angular velocities and greater touchdown velocities of both the centre of mass and the lower leg compared to maximal velocity sprinting. Based on these findings, the hurdle jump is recommended as a suitable exercise for the development
of maximum velocity sprinting due to the greater demand placed on the athlete to reverse the velocity of their centre of mass, similar peak knee extension velocities and greater ankle dorsiflexion angular velocities. Additionally, coaches are advised, if appropriate equipment are available, to monitor an athlete’s contact time during a series of hurdle jumps.

Three common themes of the thesis emerge by combining the findings of the five experimental chapters. These are: (1) implications for using ratio-based measures, (2) using ground contact time as a monitoring tool and (3) recommendations for individualised assessment and training.

Ratio based-measures are derived by diving one measure by another. Chapters 3, 4 and 5 use ratio based-measures: the acceleration time constant (τ), the reactive strength index (RSI) and reactive strength ratio (RSR), as performance indicators of sprint athletes. In Chapter 3, τ is calculated by dividing maximum velocity (v<sub>max</sub>) by maximum acceleration (a<sub>max</sub>), in Chapters 4 and 5, RSI is calculated by diving jump height by ground contact time and in Chapter 5, RSR is calculated by dividing flight time by ground contact time. Chapters 3, 4 and 5 highlight issues that can arise when ratio based-measures are used to assess and compare athletes. Measures can be misleading if they are not evaluated in the context of the original values, both numerator and denominator, that were used in their derivation. Several athletes can have identical τ, RSI or RSR values from markedly different performances or by using different performance strategies. As illustrated in Chapter 5, two athletes achieved identical values for RSI or RSR with markedly different jump heights and ground contact times suggesting different levels of ability in tolerating stretch loads and rapidly developing an impulse that would not be evident if RSI or RSR values were assessed in isolation.

Chapters 4, 5 and 7 assessed ground contact time in hopping, drop jumps, hurdle jumps and sprinting. These chapters highlight the importance of monitoring ground contact time for both performance testing and training. Chapter 5 recommends the monitoring of contact time, during reactive strength testing, and the implementation of an upper and / or lower contact time limit to reduce the impact of differing performance strategies on RSI and RSR values. More useful comparisons can be made between athletes’ RSI and RSR values if the difference in contact times between athletes is minimised. Monitoring contact time can allow the coach to effectively implement the imposed contact time limits by only including trials where the athlete’s ground contact time falls within the prescribed limit. Similarly, Chapter 7
recommends that coaches monitor contact times during the performance of hurdle jumps to ensure that athletes are performing each jump within a pre-determined range of acceptable contact times. Furthermore, in both Chapters 5 and 7, it is suggested that athletes who cannot achieve acceptably short ground contact times may need a change in the testing / training stimulus e.g. using lower hurdles or a lower drop jump box height. Conversely, athletes with no difficulty achieving short contact times can be further challenged in training by increasing the hurdle height.

Chapter 6 found that “performance adaptations” was the most prominent reason sprint coaches cited for selecting resistance training exercises for their sprint athletes. Chapters 3, 5 and 7 highlight the importance of performance testing to determine an individual athlete’s strengths and weaknesses. Chapter 3 demonstrated that using a modelling approach to assess the acceleration, maximum velocity and deceleration phases of a 100 m sprint can provide additional performance information beyond simple split times. By assessing the entire 100 m sprint performance, coaches can determine an athlete’s primary weakness and subsequently design training interventions to achieve the desired performance adaptations. Likewise in Chapters 5 and 7, assessing how an athlete achieves a given performance e.g. short contact times or high jump heights, can indicate specific strengths and weaknesses that must be addressed through training. These weaknesses in sprint and jump performance will likely vary considerably between athletes. The findings of this thesis highlight the vital role of athlete performance monitoring to facilitate the effective design of individualised athlete training.

8.2 Limitations of the Present Work
It is important to acknowledge the limitations that may have the greatest potential impact on the quality of the current programme of research.

In Chapter 3, data were drawn from publicly available data sets. These data were collected by biomechanical teams and researchers and not by the author of the present thesis. The validity of the analysis and the subsequent conclusions are dependent on the accuracy of the original input data. Furthermore, the data used were not collected using consistent measurement methods as data were compiled from events ranging from 1988 – 2017. It was assumed, however, that the data collected were accurate as the teams responsible for collecting and analysing the data were experienced biomechanists working in conjunction with the IAAF
and thus measurement errors would be minimal and therefore not affect the results and conclusions.

In Chapter 4, the hopping frequency imposed on athletes, during the repeated hops, could not accurately assess reactive strength. Thus, the relationship between reactive strength, assessed during repeated hops, and sprint performance remains unknown. Additionally, sprint horizontal forces and power were not measured directly; instead an indirect field based method was used. However, this method of profiling force-velocity-power profiling has been validated against force platform measures and thus was considered appropriate and the results acceptable.

In Chapter 6, a survey design was used to answer the primary research question: what resistance training exercises are most commonly prescribed to sprint athletes?. The use of such a design invited potential issues such as respondent’s inconsistent interpretations of specific exercises, for example, two separate coaches may use different terminology to describe the same exercise. A solution to this issue, in the present work, was to include illustrations of all of the most common resistance training exercises mentioned within the sprint literature. Furthermore, an online questionnaire was chosen in place of a structured or semi structured interview as it was considered a more practical method of gathering data from the largest possible sample of coaches. Additionally, the use of an online questionnaire ensured much quicker data analysis and thus a larger data set could be analysed in the allotted timeframe. Finally, only sprint coaches were given the opportunity to participate and thus strength and conditioning coaches that may have been working with sprint athletes could not be included. This decision was made as a database of all registered coaches in Ireland was available whereas no such database was readily available for strength and conditioning coaches.

In Chapter 7, a relatively small sample (n = 6) of male sprinters were recruited due to a limited availability of athletes / incidence of injuries and issues with the availability of the appropriate facilities. The use of a relatively small sample size comes at a cost of statistical power and thus increases the risk of type 2 errors. This risk, however, was considered and acknowledged within the discussion of Chapter 7’s findings. Furthermore, only kinematics measures were used to compare sprinting with the hurdle jump. Additional measures such as ground reaction forces and joint kinetics would have enhanced the determination of the
suitability of hurdle jumps for maximum velocity sprinting. The inclusion of such measures, however, was not possible as the necessary equipment i.e. sprint track embedded force platform, was not available.

8.3 Future Directions
While the current programme of research has addressed a series of related research questions, additional areas of research merit further investigation. Suggestions for future research could include:

1) Profiling the 100 m sprint performance of elite female sprinters during major championships to assess whether the differences between relatively faster and relatively slower sprinters are consistent with the male results. These data are currently available as many of the same biomechanical projects that measured the men’s 100 m performances also assessed the women’s 100 sprints. Additionally, the relationship between relative acceleration, maximum velocity and deceleration ability with 100 m performance merits investigation.

2) Assessing the relationship between reactive strength measured during drop jumps, from a variety of drop heights, and repeated hops to determine if both tests give the same indication of an athlete’s of reactive strength. This would be useful for coaches as there may be distinct reactive strength abilities assessed by each test that may be important to different athletes from different sports. Furthermore, the relationship between reactive strength index, assessed during hopping and in drop jumps, and joint kinetic parameters e.g. ankle and knee joint stiffness should be assessed.

3) Implementing an upper limit for contact time e.g. <0.200 s and assessing the relationship between reactive strength, assessed during drop jumps and repeated hops, and sprint performance measures and step kinematics i.e. ground contact time and step length. This would determine whether the use of stricter contact time thresholds could enhance the predictive ability of the reactive strength index.

4) Comparing the kinetics of maximum velocity sprinting to the hurdle jump. Additional kinetic measures such as joint stiffness, joint powers and the vertical and horizontal ground reaction forces would be of benefit to the programming of the hurdle jump exercise for sprint athletes. Furthermore, an in depth examination of the muscle activation patterns of sprinting and the hurdle jump exercise, using electromyography,
is merited to determine if there are further similarities between movements. This would provide additional evidence supporting the inclusion of the hurdle jump resistance training programme for the development of maximum velocity sprinting.

5) Perform a randomised controlled trial assessing the effects of specific resistance training interventions, such as plyometrics, on sprint performance. Changes in sprint performance in the acceleration, maximum velocity and deceleration phases should be assessed using a range of methods so that any change in performance can be subsequently explained by changes in sprint kinematics i.e. step length, contact time or sprint kinetics e.g. ground reaction forces, joint stiffness.
References


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Harper, D., Hobbs, S., Moore, J. (2011) 'The ten to five repeated jump test: A new test for evaluation of lower body reactive strength.', In: British Association of Sports and Exercises Sciences Student Conference, Chester,


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Appendix A: Ethical Approval

Chapter 4 & 5

Dear [Name],

Thank you for your Research Ethics application which has recently been reviewed by the Education and Health Science Research Ethics Committee.

Project Title: [Project Title], EDB: The assessment of strength, power and speed characteristics in athletes

Principal Investigator: [Name]

Additional Investigators: [List of names]

Recommendation: Your ethics application has been approved.

Date of Approval: [Date]

[Name]

Research Ethics Committee
Chapter 6

Dear [Name],

Thank you for your Research Ethics application which was recently reviewed by the Education and Health Science Research Ethics Committee. The recommendations of the Committee are outlined below:

Project Title: [Title]

**Approval Details:**
- **Research Design:**
  - Address of building: unstructured interviews
  - Address of building: unstructured interviews

- **Data Collection:**
  - Address of building: unstructured interviews
  - Address of building: unstructured interviews

- **Subject Number & Selection Procedures:**
  - Up to 50 subjects for the questionnaire and 10 in the unstructured interviews

- **Changes in Supporting Documentation:**
  - Address of building: unstructured interviews
  - Address of building: unstructured interviews

Please note that as Principal Investigator of this project you are required to submit a Research Compliance Report Form (attached) on completion of the research study.

Yours sincerely,

[Name]

[Name]

[Name]

[Name]

[Name]

Chapter 7

Dear [Name],

Thank you for your Research Ethics application which was recently reviewed by the Education and Health Science Research Ethics Committee. The recommendations of the Committee are outlined below:

Project Title: [Title]

**Approval Details:**
- **Research Design:**
  - Address of building: unstructured interviews
  - Address of building: unstructured interviews

- **Data Collection:**
  - Address of building: unstructured interviews
  - Address of building: unstructured interviews

- **Subject Number & Selection Procedures:**
  - Up to 50 subjects for the questionnaire and 10 in the unstructured interviews

- **Changes in Supporting Documentation:**
  - Address of building: unstructured interviews
  - Address of building: unstructured interviews

Please note that as Principal Investigator of this project you are required to submit a Research Compliance Report Form (attached) on completion of the research study.

Yours sincerely,

[Name]

[Name]

[Name]
Appendix B: Subject Informed Consent Form

Informed Consent

I confirm that all aspects of my participation have been fully explained to my satisfaction. I am fully aware of the risks of the study and know that I can withdraw from the study at any time should I choose to.

I confirm that I meet the selection criteria of:

- Regular resistance training
- Not currently injured
- Above a minimum age of 18
- Have no existing medical ailment which may deter them from the study

AGREEMENT TO CONSENT – If you agree to participate in this research study please sign below. You will be issued with a photocopy of this form, for your own records.

I, ..............................(PRINT NAME) consent to participate on an anonymous basis, in the research study outlined above.
Appendix C: Subject Pre-Test Questionnaire

SUBJECT PRE-TEST QUESTIONNAIRE

NAME .............................................. Ref. No. ......................
Date of Birth ................................. Age: ..............................
Test procedure .............................. Email Address ............................

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

Please tick appropriate box

<table>
<thead>
<tr>
<th></th>
<th>YES</th>
<th>NO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Has the test procedure been fully explained to you?</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Any information contained herein will be treated as confidential

Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?
Do you feel pain in your chest when you do physical activity? □ □ □

In the past month, have you had chest pain when you were not doing physical activity? □ □ □

Do you lose your balance because of dizziness or do you ever lose consciousness? □ □ □

Do you have a bone or joint problem that could be made worse by a change in your physical activity? □ □ □

Is your doctor currently prescribing drugs for your blood pressure or heart condition? □ □ □

Do you know of any other reasons why you should not undergo physical activity? This might include severe asthma, diabetes, a recent sports injury, or serious illness. □ □ □

Have you any blood disorders or infectious diseases that may prevent you from providing blood for experimental procedures? □ □ □

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

I ………………………………. declare that the above information is correct at the time of completing this questionnaire Date ……/……/…….

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

If you have answered YES to one or more questions:
Talk with your doctor in person discussing with him/her those questions you answered yes. Ask your doctor if you are able to conduct the physical activity requirements.

Doctor’s signature ……………………………………….. Date ……/……/…….

Signature of Experimenter……………………………… Date ……/……/……
Appendix D: Questionnaire used in Chapter 6

* 1. Title: The Resistance Training Practices of Sprint Coaches

Thank you for your interest in this research. Completion of this survey should take you between 7 and 10 minutes. There are a number of questions to be completed which range from ticking a box, to giving your views and opinions on resistance training and speed development. Please do not dwell on questions and try answering every question – if you are not sure, go with your initial reaction. You will also be given the opportunity to add any comments or opinions which you feel are important but weren’t touched on in this survey.

This questionnaire has been ethically approved and anonymity and confidentiality is ensured. Please note you are under no obligation to participate in this study and you are free to withdraw from the study at any point.

If you have further questions regarding this research please feel free to get in touch with the email address provided below.

Yours sincerely,

Robin Healy
PhD Researcher
Physical Education and Sport Sciences Department
University of Limerick
robin.healy@ul.ie

This research project has been approved by the University of Limerick’s Faculty of Education and Health Sciences Research Ethics Committee. Ethics approval code: 2013_02_01_EHS

By ticking the ‘agree’ box below you are adhering to the following points and may participate in this study.

• I have read and understood the participant information provided above.

• I understand what the project is about, and what the results will be used for.

• I am fully aware of all the procedures involving myself, and of any risks and benefits associated with the study.

• I know that my participation is voluntary and that I can withdraw from the study at any stage without giving reason.

☐ I Agree
**Coach Background Information**

1. **Are you male or female?**
   - Male
   - Female

2. **What disciplines are the athletes that you coach?**
   - Sprints & Hurdles
   - Middle and Long Distance
   - Jumps
   - Multi-events
   - Throws

3. **Where are you currently coaching (Country)?**
   - [ ]

4. **How many years have you been coaching sprint athletes?**
   - [ ]

5. **What is the highest level of the athletes you have coached previously or are currently coaching?**
   - International
   - National
   - Provincial
* 7. If you currently hold a coaching certificate in athletics please specify at what level.

If certificate is from outside of Athletics Ireland please specify in "Other" box provided.

If you do not hold a certificate select "NA"

- Athletics Leader
- Assistant Coach
- Level 1
- Level 2
- Level 3
- NA
- Other (please specify)

* 8. If you currently hold a certification in strength and conditioning please specify which certification you hold.

If you do not hold a certificate select "NA"

- UKSCA accredited
- NSCA Certified Strength and Conditioning Specialist
- NA
- Other (please specify)
Coaches Views on Resistance Training

9. Resistance training is any form of structured physical training where the body must resist, overcome or bear an external load.

For the purposes of this questionnaire resistance training includes weight training and plyometric or jump type training.

Resistance training does not include:
Core training
Flexibility training
Theraband or resisted band training
Bodyweight training

Do your athletes currently perform resistance training?

- Yes
- No
Coaches Views on Resistance Training

* 10. How important do you believe resistance training is to speed development?
   - [ ] Not important
   - [ ] Somewhat important
   - [ ] Important
   - [ ] Very important

* 11. In relation to speed development why do you think your athletes should perform resistance training?


* 12. Who is involved with the prescription of resistance training exercises?
   - [ ] Only you (the coach)
   - [ ] Another coach only
   - [ ] The strength and conditioning coach only
   - [ ] A combination between you (the coach) and the strength and conditioning coach
   - [ ] Other (please specify)


* 13. Where do you source the majority of your information regarding the prescription of resistance training exercises?
   - [ ] Research articles
   - [ ] Previous experience
   - [ ] The internet
   - [ ] Books
   - [ ] Other coaches
   - [ ] Coaching conferences or seminars
   - [ ] Coaching courses
   - [ ] From the athletes
   - [ ] Other (please specify)
Illustrated below are several traditional training exercises

Back Squat

Front Squat

Deadlift

Split Squat
14. Of the traditional training exercises illustrated above which do your athletes perform regularly?

- [ ] Back Squat
- [ ] Split Squat
- [ ] Hip Thrust
- [ ] Front Squat
- [ ] Step Up
- [ ] Romanian Deadlift (RDL)
- [ ] Deadlift
- [ ] Barbell Lunge
- [ ] Other or variations of any of the above exercises (please specify)
* 15. If time were limited and you could only prescribe TWO traditional resistance training exercises which exercises would you choose?

- [ ] Back Squat
- [ ] Front Squat
- [ ] Deadlift
- [ ] Split Squat
- [ ] Step Up
- [ ] Barbell Lunge
- [ ] Hip Thrust
- [ ] Romanian Deadlift (RDL)
- [ ] Other (please specify)

* 16. Why have you chosen these exercises?
Illustrated below are several ballistic resistance training exercises

Kettlebell Swings

Jump Squats

High Pull

Power Clean
* 17. Of the ballistic training exercises illustrated above which do your athletes perform regularly?

- [ ] Kettlebell Swings
- [ ] Power Clean
- [ ] Jump Squats
- [ ] Power Snatch
- [ ] High Pull
- [ ] Other or variations of the above exercises (please specify)

- [ ]

* 18. If time were limited and you could only prescribe TWO ballistic training exercises which exercises would you choose?

- [ ] Kettlebell Swings
- [ ] Power Clean
- [ ] Jump Squats
- [ ] Power Snatch
- [ ] High Pull
- [ ] Other (please specify)

- [ ]

* 19. Why have you chosen these exercises?

- [ ]
Illustrated below are several plyometric or jump type exercises

Squat Jump

Countermovement Jump

Drop Jump

Box Jump
* 20. Which of the plyometric exercises illustrated above do your athletes perform regularly?

☐ Squat Jump  ☐ Box Jump  ☐ Broad Jump
☐ Countermovement Jump  ☐ Drop to Box Jump  ☐ Repeated Broad Jump
☐ Drop Jump  ☐ Hurdle Jump  ☐ Ankle Hops
☐ Other or variations of any of the above exercises (please specify)

* 21. If time were limited and you could only prescribe TWO plyometric resistance training exercises which exercises would you choose?

☐ Squat Jump
☐ Countermovement Jump
☐ Drop Jump
☐ Box Jump
☐ Drop to Box Jump
☐ Hurdle Jump
☐ Broad Jump
☐ Repeated Broad Jump
☐ Ankle Hops
☐ Other (please specify)

* 22. Why have you chosen these exercises?
23. Thank you for your participation. If you have any comments or points to add with respect to resistance training exercises please enter below. Otherwise click Done
Influence of Reactive and Maximum Strength Indicators on Sprint Performance

Robin Healy, Carol Smythe, Ian C. Kenyon, and Andrew J. Harrison
Department of Physical Education and Sport Sciences, University of Limerick, Limerick, Ireland

Abstract
Healy, R., Smythe, C., Kenyon, I. C., and Harrison, A. J. Influence of reactive and maximum strength indicators on sprint performance. J Strength Cond Res 28(11): 3000-3009, 2014. The primary aim of this study was to assess the relationship between reactive and maximal strength measures with 40 m sprint performance and mechanical properties. Fourteen male and 14 female sprinters participated in this study. On the first day, subjects performed 40 m sprints with 10 m split times recorded in addition to maximal theoretical velocity, maximal theoretical force and peak horizontal power, which were calculated from force-velocity relationships. On the second day, subjects performed isometric mid-thigh pulls (IMTPs) with peak force (PF) and relative PF calculated, drop jumps (DJIs) and vertical hopping where the reactive strength index (RSI) was calculated as jump height (JH) divided by contact time (CT). Pearson correlations were used to assess the relationships between measures and independent samples t-tests were used to assess the differences between men and women. No significant correlations were found between DJ and hopping RSI and sprint measures. A significant strong positive correlation was found between IMTP PF and peak horizontal power in men only ($r = 0.81$). The male sprinters performed significantly better in all recorded measures apart from hopping (CT, JH and RSI) and DJ (CT) where no significant differences were found. The lack of association between reactive and maximal strength measures with sprint performance is potentially because of the tasks prolonged CTs relative to sprinting and the inability to assess the technical application of force. Several methods of assessing reactive strength are needed that can better represent the demands of the distinct phases of sprinting e.g., acceleration, maximum velocity.

Introduction
Sprint performance is critical to success in various team and individual sports. In track events, rapid acceleration and high maximum velocity are crucial to race performance (26, 33). The 100 m sprint can be broken down simply into 3 main phases: the acceleration phase, the maximum velocity phase, and the deceleration phase (9). Furthermore, each phase can be subdivided in various ways e.g., the initial acceleration phase (0-12 m) and the main acceleration phase (12-35 m) (21). Consequently, sprinting can be considered a multidimensional skill with different kinematic and kinetic requirements during the distinct phases ($9$). Accordingly, different strength capabilities play relatively larger roles throughout the performance of a sprint (26).

A novel field method of profiling athletes’ horizontal force-velocity relationship over 40 m has recently been developed (32). Mechanical variables such as the theoretical maximum horizontal component of ground reaction force ($F_h$), theoretical maximum horizontal velocity ($v_h$) and the maximum horizontal mechanical power (Pmax) produced can all be measured during accelerating performance (32). Research on sprint athletes has found that maximum velocity and mean 100-m velocity were both very strongly correlated with Pmax (33). In contrast, Slawinski et al. (35) found no correlation between Pmax and 100-m time, whereas $v_h$ had a very large negative correlation with Pmax in world-class athletes. It is suggested that Pmax may be more likely related to performance over shorter distances i.e., 40 or 60 m where fatigue is limited (35). This is supported by Rabita et al. (28) who found that maximal velocity achieved over 40 and 40 m performance in elite and sub elite sprinters had an almost perfect positive and very large positive correlation with Pmax and $v_h$, respectively.

The ground contact phase of sprinting involves the coupling of an eccentric contraction with a concentric contraction. This is termed the stretch shortening cycle (SSC) and it is frequently used in many additional sports movements e.g., the leg extensor muscles during jumping and hopping (27). The SSC has been classified as either fast, where contact times (CTs) $< 0.250$ seconds, or slow, where CTs $> 0.250$ seconds (34). Therefore, sprinting is considered a fast SSC activity as a sprinter’s CT after the initial block push off is below 0.250 seconds for each step with CTs
Reactive Strength Index: A Poor Indicator of Reactive Strength?
Robin Healy, Ian C. Kenny, and Andrew J. Harrison

Purpose: To assess the relationships between reactive strength measures and associated kinematic and kinetic performance variables achieved during drop jumps. A secondary aim was to highlight issues with the use of reactive strength measures as performance indicators. Methods: Twenty-eight national- and international-level sprinters, 14 men and 14 women, participated in this cross-sectional analysis. Athletes performed drop jumps from a 0.3-m box onto a force platform with dependent variables contact time (CT), landing time, push-off time, flight time, jump height (JH), reactive strength index (RSI, calculated as JHF/CT), reactive strength ratio (RSR, calculated as flight time/CT), and vertical leg-spring stiffness recorded. Results: A Pearson correlation test found very high to near-perfect relationships between RSI and RSR (r = 0.91–0.97), with mixed relationships between RSI, RSR, and the key performance variables (mm: r = -0.86 to -0.71 between RSI/RSR and CT, r = 0.70 to 0.00 between RSI/RSR and JH; women: r = -0.85 to -0.56 between RSI and CT, r = 0.71 between RSI and JH). Conclusions: The method of assessing reactive strength (RSI vs RSR) may be influenced by the performance strategies adopted, that is, whether athletes achieve their best reactive strength scores via low CTs, high JHs, or a combination. Coaches are advised to limit the variability in performance strategies by implementing upper and/or lower CT thresholds to accurately compare performances between individuals.

Keywords: drop jump, stretch-shortening cycle, reactive strength ratio, contact time, jump height

The stretch-shortening cycle (SSC) is utilized in many sporting movements, for example, in the leg extensor muscles during the ground contact phases of running, sprinting, jumping, and hopping movements. 

The SSC of muscle function has been characterized by an eccentric (lengthening) muscle action quickly followed by a concentric (shortening) muscle action. In this state, greater positive work and more power were generated during the concentric muscle action relative to that of an isolated concentric muscle action. 

Several mechanisms have been proposed to explain the greater positive work performed by the muscle: an increase in the time available to develop force, the storage and subsequent utilization of elastic energy in the series elastic element of a muscle fiber; and a mechanism that enhances the activation of motor neurons during concentric muscle action. The relative contribution of each potential mechanism will vary across movement type, as factors such as tendon loading and SSC duration are not identical in all SSC activities. Therefore, generalizations about the SSC should not be made from 1 specific muscle and from 1 condition only.

Direct methods using in vivo force measurements have been employed to characterize SSC function in isolated muscles during human locomotion. Based on these methods, 2 fundamental conditions have been identified for effective SSC function: a well-timed preactivation of the muscle prior to impact, a short and fast eccentric phase, and a near-immediate transition between eccentric and concentric phases. Consequently, coaches have attempted to evaluate specific sporting movements that utilize the SSC. To accomplish this, the concept of reactive strength was developed. 

Reactive strength has been described in numerous ways throughout the literature. The most commonly used definition is the capacity of an athlete to bear a stretch load and subsequently switch rapidly from an eccentric to concentric muscle action. Other authors have focused on a more mechanical definition, that is, an athlete’s ability to rapidly generate force under high eccentric load. Regardless, reactive strength has been assessed during various sporting movements, for example, drop jumps, vertical drills, and counter-movement jumps.

Within the literature, SSCs have been generally classified as either fast or slow based on contact times (CTs) <0.250 second and >0.250 second, respectively. This paper exclusively examines reactive strength assessed during a fast SSC movement, that is, the drop jump, where an athlete drops from a set height and upon landing performs a vertical jump at maximal effort. The drop jump can be broken into 2 distinct temporal phases: contact phase, which can be further subdivided into loading and push phase (Tpush), and the flight phase, that is, time spent in the air. The manipulation of these 2 temporal phases has led to the identification of 3 drop jump techniques: the bounce drop jump, where an athlete attempts to minimize CT, which occurs at the expense of higher jump heights (JHs); the countermovement drop jump, where an athlete attempts to achieve maximal flight time (FT) and thus maximal JH, which results in much longer CTs than the aforementioned methods; and the combination technique, whereby an athlete attempts to get off the ground as quickly as possible while also aiming to jump as high as possible.

It has been suggested that reactive strength can be assessed in the drop jump using the reactive strength index (RSI) performed using the combination technique. Several authors have proposed that the RSI is an effective means of assessing the performance of an SSC task and can also provide an indication of an athlete’s vertical leg-spring stiffness (kvert). In the literature, RSI has been calculated using 2 calculation methods: the JH in a drop jump, generally derived from FT, divided by the CT; or the FT of the jump divided by the CT. The latter method has sometimes been referred to as the flight-to-CT ratio or simply the reactive strength ratio (RSR). The key distinctions between RSI and RSR values, from a calculation perspective, are highlighted in Table 1. The...
Appendix F: Proof of Acceptance of Chapter 6