A cross-sectional correlational study of the Dynamic Strength Index with the slope of the Force-velocity profile in the loaded countermovement jump.

by

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ABSTRACT

Strength and conditioning professionals require time efficient and effective means of evaluating the characteristics of muscular force expression among athletes. Two such methods, the DSI and the lower-body F-v profile, are used to guide the direction of training towards more velocity-dependent (i.e. ballistic strength) methods of training or towards more force-dependent (i.e. maximal strength) methods of training. While the use of both of these protocols have been recommended in the literature for a similar purpose, little research has been done in evaluating the relationship between the results of both protocols. Eighty-six resistance-trained individuals were recruited to perform both the DSI testing and F-v profile testing protocols to evaluate this relationship, as well as relationships between the components that compose each test. Correlations were calculated between DSI, F-v profile slope, countermovement jump (CMJ) peak force (PF), isometric mid-thigh pull (IMTP) PF, and CMJ peak velocity (PV) across a series of loading conditions from an unloaded CMJ to an additional 100% bodyweight (BW) CMJ condition. No significant correlations were found between the DSI value and the F-v profile slope. Significant correlations ($p<0.05$) were found between the DSI and CMJ/IMTP PF. Significant correlations ($p<0.05$) were found between CMJ/IMTP PF and measures of CMJ PV across the loading conditions. These results suggest that the DSI is not correlated to the F-v profile slope, however measures of performance used for the evaluations are significantly correlated.

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LIST OF TERMS

+100% BW CMJ PV	+100% bodyweight countermovement jump peak velocity
ASIS	Anterior superior iliac spine
CP	Creatine phosphate
ATP-CP	Adenosine triphosphate – creatine phosphate
BW CMJ PV	Bodyweight countermovement jump peak velocity
CMJ	Countermovement jump
CMJ PF	Countermovement jump peak force
CMJ PV	Countermovement jump peak velocity
CSA	Cross-sectional area
DSI	Dynamic strength index
F-v	Force-velocity
IMTP	Isometric mid-thigh pull
IMTP PF	Isometric mid-thigh pull peak force
LESS RT	Landing error scoring system real-time
L-t	Length-tension
MTU	Musculotendinous unit
Pmax	Maximal power
RFD	Rate of force development
SEC	Series elastic component
SJ	Squat jump
SSC	Stretch shortening cycle

CHAPTER 1 – SCIENTIFIC FRAMEWORK

1.1 Introduction

High levels of muscular strength have been shown to underpin performance in numerous athletic tasks (Comfort et al., 2017) including performance in throwing, running, and jumping (Suchomel, Nimphius, & Stone, 2016). As strength and conditioning methods have continued to evolve along with the physical demands of competition in sport, there has been increased relevance regarding the investigation of high-intensity ballistic actions (Jiménez-Reyes, Samozino, Pareja-Blanco, et al., 2017). Research has shown that high amounts of force generation in a short amount of time is important to many sport specific and dynamic tasks (Dos'Santos et al., 2016). This has led exercise professionals to develop training programs in order to maximize specifically desired characteristics of muscular strength.

Strength training is a critical stimulus for inducing changes in muscular size, strength, and power (Jovanovic & Flanagan, 2014), with individualized training programs having been found to have a higher impact on specific task performance than generically designed training programs (Jiménez-Reyes, Samozino, Pareja-Blanco, et al., 2017). Establishing a means of measuring muscular strength is an essential component of monitoring the effectiveness of strength training programs, with assessment of important biomechanical characteristics being referred to as a strength diagnosis (Jiménez-Reyes, Samozino, Pareja-Blanco, et al., 2017; Thomas, Jones, & Comfort, 2015). The most common means of compiling a strength diagnosis is to directly measure an athlete's maximal strength by performing an exercise-specific one-repetition maximum (1RM), as relative percentages of the 1RM are usually prescribed as training intensity in resistance training programs (Suchomel et al., 2016). Despite the popularity of the direct method several issues with its evaluation have been noted including increased chance of

muscle pain or injury related to muscle tension and unstable posture in inexperienced athletes (Bazuelo-Ruiz et al., 2015; Picerno et al., 2016) as well as impracticality in larger groups (Jovanovic & Flanagan, 2014). For these reasons the direct method has been contraindicated in some populations. The issues associated with direct 1RM determination and the advent of long-term athlete development and earlier specialization has driven the need for less invasive means of evaluating strength characteristics (McKay, Broderick, & Steinbeck, 2016).

Measurement of force on force platforms, considered the gold standard of force data collection (Cronin, Hing, & McNair, 2004; García-Ramos et al., 2015; Jiménez-Reyes, Samozino, Pareja-Blanco, et al., 2017) have become popular among strength and conditioning practitioners. In particular, measurements of isometric strength have been found to show relationships between maximum isometric strength and dynamic performance characteristics including 1RM tests, acceleration ability, and vertical jump ability (Dos'Santos, Thomas, Comfort, McMahon, Jones, et al., 2017; McGuigan, Winchester, & Erickson, 2006; Thomas, Jones, & Comfort, 2015; Wang et al., 2016). Despite their popularity some issues have been identified with the use of force platforms including their sensitivity to extraneous vibration when not properly mounted rendering them essentially immobile (Cronin et al., 2004; García-Ramos et al., 2015) and have high costs that put them outside of the budget for many strength and conditioning facilities (Cronin et al., 2004; García-Ramos et al., 2015). The relative inaccessibility of force platforms has caused a proliferation of technologies in the market to measure aspects of muscular performance. One such device, the linear position transducer, has the advantage of low cost, simplicity of use, versatility, and ease of transport (García-Ramos et al., 2015). These devices have shown good relationship in their measurements of force, velocity,

and power when compared to force platforms (Garnacho-Castaño, López-Lastra, & Maté-Muñoz, 2015).

Both force platforms and linear position transducers can be used to evaluate characteristics of strength performance to guide training programs for individual athletes. Evaluated on a force platform, the Dynamic Strength Index (DSI) examines the relationships between dynamic and isometric peak force and is expressed as a ratio of ballistic peak force : isometric peak force, allowing a comparison of dynamic-force capability of an athlete in relation to their maximum-force capability (Comfort et al., 2017; Thomas, Jones, & Comfort, 2015). Linear position transducers can be used to establish an exercise specific Force-velocity (F-v) profile (Bosquet, Porta-Benache, & Blais, 2010; García-Ramos et al., 2016; Jovanovic & Flanagan, 2014), which is possible due to the F-v relationship. The F-v relationship states that the muscle-force generating capacity decreases as contraction velocity increases, resulting in an inverse relationship between muscle force production and contraction velocity (Cronin, McNair, & Marshall, 2003; Giroux, Rabita, Chollet, & Guilhem, 2015; Harry G. Banyard, Nosaka, Vernon, & Haff, 2017; Jovanovic & Flanagan, 2014). The F-v profile represents the dynamic capability of the neuromuscular system to function under various loading conditions with significant implications in movement performance (Cronin et al., 2003) and can be evaluated by measuring velocity characteristics of loaded ballistic exercises (Jovanovic & Flanagan, 2014; Mundy, Lake, Carden, Smith, & Lauder, 2016).

Both the DSI and the F-v profile can be used to guide the direction of strength training programming to favour ballistic movements or maximal strength exercise in an attempt to maximize the desired variables of athletic performance (Jiménez-Reyes, Samozino, Pareja-Blanco, et al., 2017; P. Samozino et al., 2014; Sheppard, Cormack, Taylor, McGuigan, &

Newton, 2008; Thomas, Jones, & Comfort, 2015). Pending on the value of the DSI or the slope of the F-v profile the practitioner can prescribe more maximal strength focused or a more ballistic strength focus during exercise programs (Comfort et al., 2017; P. Samozino et al., 2014; Thomas, Jones, & Comfort, 2015).

There exists a gap in the literature regarding the relationship between the DSI and the slope of the F-v profile in lower body musculature. While the slope of the F-v relationship is described as being useful to guide exercise professionals regarding focus on maximal strength development or to develop ballistic characteristics for individualized training programs, to the authors' knowledge there is no research regarding numeric values of the slope that could be used to more specifically guide training decisions. The purpose of this cross-sectional correlational study is to determine if a relationship exists between established values of the DSI (Comfort et al., 2017; Thomas, Jones, & Comfort, 2015) and the slope of the F-v relationship in a resistance-trained population.

1.2 Review of Literature

1.2.1 Background. Defined as the ability to exert force against an object or resistance, maximal muscular strength is an underlying factor in all aspects of sport performance (Brady, Harrison, & Comyns, 2018; Suchomel et al., 2016). High levels of strength have been shown to underpin performance in numerous athletic tasks including performance in throwing, running, and jumping (Comfort et al., 2017; Suchomel et al., 2016). Depending on an individual's sport or event, an athlete may be required to exert large forces against gravity to manipulate their own body mass (e.g. sprinting, gymnastics, jumping events), manipulate their own plus an opponents' body mass (e.g. American football, wrestling), or manipulate an implement or projectile (e.g. baseball, weightlifting, throwing events) with muscular strength being a related factor in

performance of all these tasks (Suchomel et al., 2016). Success in sport can be affected by an athletes strength levels, and when comparing evidence of success between athletes of relatively homogenous sport skill stronger athletes tend to perform better in comparison to weaker athletes (Suchomel et al., 2016; Thomas, Dos'Santos, & Jones, 2017).

Muscular power (power = work/time) is the product of force and velocity (Feeney, Stanhope, Kaminski, Machi, & Jaric, 2016), and is also important for sport performance. The time in which an athlete has to generate force is often limited in sport situations, and as such the ability to quickly generate high amounts of force in a short amount of time is important to many sport specific and dynamic tasks (Dos'Santos et al., 2016). Representing the ability to produce force at specific velocities under the limitations of cross-bridge cycling, power is the product of muscle force and muscle contraction velocity (Haug, Spratford, Williams, Chapman, & Drinkwater, 2015). Research has shown that a high amount of relative strength is a precursor to being able to generate high amounts of muscular power (Cormie, McGuigan, & Newton, 2011b; Dos'Santos, Thomas, Comfort, McMahon, & Jones, 2017). High amounts of relative strength (defined as the strength that an individual possesses in relation to their own body mass) are particularly important in sporting tasks that require a high amount of force generation in relatively short time intervals (Dos'Santos, Thomas, Comfort, McMahon, & Jones, 2017). The strength levels of athletes always dictate their maximal muscular power (Pmax), which is supported by the abundance of research and empirical observations in the strength-power capabilities in both elite and sub-elite athletes (Cormie et al., 2011b). This is due to the fact that stronger individuals possess favourable neuromuscular characteristics that form the basis for superior power production (Cormie et al., 2011b).

1.2.2 Intrinsic properties of skeletal muscle. The F-v relationship is an intrinsic property of skeletal muscle which governs the muscles ability to express force and velocity characteristics. The F-v relationship states that muscle force-generating capacity decreases as contraction velocity increases, which results in an inverse relationship between muscle force production and muscle contraction velocity (Alcazar et al., 2018; Banyard, Nosaka, Vernon, & Haff, 2017; Cronin et al., 2003; Giroux et al., 2015; Jovanovic & Flanagan, 2014). This is true for a given muscle/muscle group that is activated at a constant level due to the time constraints imposed by actin-myosin cross-bridge cycling (i.e. it takes a fixed amount of time for cross-bridges to cycle), and that the total number of cross-bridges attached decreases with an increasing velocity of muscle shortening (Cormie, McGuigan, & Newton, 2011a). In a practical sense as long as maximal effort is given for the concentric phase of a lift, heavier loads cannot be lifted with the same velocity as lighter loads (Banyard et al., 2017). This relationship is of interest as it allows practitioners to selectively assess force, velocity, and power generating capacity of muscular contractions and quantifies the ability of the neuromuscular system to function under various loading conditions (Cormie et al., 2011a; García-Ramos, Feriche, Pérez-Castilla, Padial, & Jaric, 2017; Zivkovic, Djuric, Cuk, Suzovic, & Jaric, 2017). This has been investigated in several resistance training exercises including the leg press, bench press, prone pull-up, half squat, and full squat exercises (Banyard et al., 2017; García-Ramos et al., 2017). This relationship is of an approximately linear shape, with the relationship parameters directly revealing the capabilities of muscle groups to develop high force, velocity, and power (Banyard et al., 2017; Zivkovic et al., 2017). When discussing the F-v relationship, force capabilities represent the ability to develop very high levels of force at lower velocities whereas velocity

capabilities represent the ability to produce force at very high contraction velocities (Pierre Samozino, Riviere, Rossi, Morin, & Jimenez-Reyes, 2017).

The Length-tension (L-t) relationship is an intrinsic property of skeletal muscle which also governs the muscles ability to express force and velocity characteristics (Cormie et al., 2011a). The length-tension relationship influences the ability of muscle fibres to develop force and plays an important role in maximal muscular power production, with the ability of skeletal muscle to generate force being critically dependent on sarcomere length (Cormie et al., 2011a). As power is heavily influenced by maximal contraction velocity, a longer muscle fibre can generate a higher Pmax (Cormie et al., 2011a). Research has shown that the greatest potential for muscular force production on the activation of the cross-bridge cycle exists when the sarcomere length provides an optimal overlap between the actin and myosin filaments (i.e. the optimal length) (Cormie et al., 2011a). At the optimal length cross-bridge interaction is maximized and allows for the greatest levels of active tension development, while force production is impaired when sarcomere lengths are shortened below their optimal length or stretched beyond their optimal length (Cormie et al., 2011a). When the sarcomere is stretched there is a reduced capacity for force production because cross-bridge interaction is decreased due to less overlap between actin and myosin filaments, and when the sarcomere is shortened the overlap of actin filaments from the opposite end of the sarcomere coupled with the compression of the myosin filament as it comes in contact with the z-disk reduces the potential for force production (Cormie et al., 2011a).

It should also be noted that the history of muscular contraction and the condition of the muscle environment for each muscle may influence the expression of muscular force. An athletes acute history of muscle contraction (e.g. fatigue, temperature, changes in hormone

milieu) may influence the expression of muscular force and power (Cormie et al., 2011a; Suchomel, Nimphius, Bellon, & Stone, 2018). During a fatigue state numerous properties of muscle are altered including ionic changes in the action potential, extracellular ions, and intracellular metabolites with each of these affecting maximal muscular power through impairing force generation and/or the velocity of shortening during contractions (Cormie et al., 2011a; B. F. de Salles et al., 2009). Intramuscular acidosis, for example, significantly relates to loss of force and tetanic tension in skeletal muscle (Grgic, Lazinica, Mikulic, Krieger, & Schoenfeld, 2017). Alterations in muscle temperature also influence maximal power production as it has been shown that Pmax, maximal velocity, maximal force, and the rate of force development (RFD) all decrease with a decrease in muscle temperature (Cormie et al., 2011a). It should be noted that a combination of factors co-existing during fatigue result in even greater impairment than what has been observed for fatigue factors individually (Cormie et al., 2011a).

The amount of rest or recovery time has been shown to influence the muscles ability to express force and has been determined to be a key variable of resistance training as it influences fatigue and muscle recovery (B. F. de Salles et al., 2009; Grgic et al., 2017; Maté-Muñoz et al., 2018). During rest time several mechanisms take place including the replenishment of the ATP-CP system, the buffering of hydrogen from glycolytic energy metabolism, and removal of lactate that as accumulated in the muscle (B. F. de Salles et al., 2009; Grgic et al., 2017), all of which have an impact on a muscles ability to express force. It has been shown that rest interval time has an impact on intensity and volume during training as restricting rest intervals may not allow for full restoration of ATP and CP, with shorter rest intervals having a negative effect on performance (i.e. reduction in training volume) and increase in metabolic demand (Grgic et al., 2017). Longer rest intervals, however, allow for higher training volume, regeneration of

phosphate bonds, and are less metabolically demanding (Grgic et al., 2017). While it has been suggested in the literature that a one-minute rest interval may be sufficient in some cases to maintain strength expression in a training session, rest intervals of three to five minutes may be more reliable to maintain muscular strength performance (B. F. de Salles et al., 2009). In regards to muscular power performance it is recommended that rest times should closely match the time required to for replenishment of phosphocreatine, which requires a minimum of four minutes of recovery (B. F. de Salles et al., 2009; Hernández Davó, Botella Ruiz, & Sabido, 2017). Interestingly, some authors have shown that rest intervals of one, two, three, or four minutes are enough to maintain power output throughout a training session, particularly in stronger populations (B. F. de Salles et al., 2009; Nibali, Chapman, Robergs, & Drinkwater, 2013a). This evidence suggests that an individuals' level of strength highly influences the rest interval that is required to sustain power output throughout a training session (B. F. de Salles et al., 2009), which further supports the importance of high levels of muscular strength for muscular power performance.

1.2.3 Architectural factors that affect muscle force production. There are several architectural components of skeletal muscles which impact their ability to generate force including cross sectional area (CSA), muscle fiber pennation angle, fiber type distribution, and tendinous stiffness.

Muscle CSA, which is determined by both the size and number of muscle fibres (Miller, MacDougall, Tarnopolsky, & Sale, 1993), has a strong relationship with force production capability (Suchomel et al., 2018). Muscles that have a greater CSA have the potential to generate higher amounts of force (Miller et al., 1993; Suchomel et al., 2018). This is true with whole muscles and with individual muscle fibres, as the maximal force generated by a single

muscle fibre is directly proportional to its CSA regardless of muscle fibre type (i.e., Type I or Type II) (Cormie et al., 2011a). Fiber type contribution to the muscle area can affect the ability of a muscle to generate force, with Type II fibres having a greater capacity for force generation per unit CSA compared to Type I fibres (Cormie et al., 2011a). When measuring specific tension (i.e., force per unit CSA) force generating capability is affected by fibre type distribution and the amount of non-contractile tissue present in the muscle (Miller et al., 1993). The F-v properties of a muscle are also determined by the fibre type contribution to whole muscle area, with a higher concentration of Type II fibres being associated with better performance across the F-v spectrum (Cormie et al., 2011a). As Pmax is heavily influenced by maximal muscular force, muscles with a greater CSA can generate a higher Pmax (Cormie et al., 2011a).

Tendinous stiffness (i.e. the relationship between a given applied force and the amount of stretch the tissue undergoes) affects muscular strength and power as tendinous structures can act as an energy re-distributor and power amplifier (Cormie et al., 2011a; Kalkhoven & Watsford, 2018; Suchomel et al., 2018). This is generally believed to be due to the storage and utilization of elastic energy (Cormie et al., 2011a). As an active musculotendinous unit (MTU) is stretched, mechanical work absorbed by the MTU can be stored in part as potential energy in the series elastic component (SEC) of muscle (i.e. fibre cross-bridges, aponeurosis, and tendon) and some of this energy can then be used to increase mechanical energy and positive work during a subsequent concentric contraction (Cormie et al., 2011a). Muscle fascicle behaviour is affected by the interaction between the contractile and elastic elements of the MTU with the intrinsic compliance of tendon impacting these interactions (i.e. affecting the amount of fascicle displacement). It has been frequently suggested that higher tendinous stiffness is beneficial for

fast stretch-shortening cycle (SSC) activities that involve a high movement velocity (Cormie et al., 2011a; Kalkhoven & Watsford, 2018).

Muscle fiber pennation angle affects a muscles ability to generate force. When a muscle has increased pennation angles more sarcomeres can be arranged in parallel (i.e. more tissue can attach to a given area of an aponeurosis or tendon) and therefore the muscle can produce more force (Cormie et al., 2011a; Suchomel et al., 2018). Additionally, increased in pennation angle allows for muscle fibres to shorten less for a given tendon displacement, increasing the likelihood that a fibre with a greater pennation angle operates closer to its optimum length (Cormie et al., 2011a). While increased fibre pennation angle is advantageous for maximal force production, a greater pennation angle is associated with slower contraction velocities and may negatively impact maximal contraction velocity (Cormie et al., 2011a). It should be noted that the increase in maximal force is theorized to have a greater impact on Pmax than decreases to maximal contraction velocity that are brought through an increase in pennation angle (Cormie et al., 2011a).

1.2.4 Neurological characteristics of muscular force production. There are several neurological factors that influence the ability of a muscle to generate force including motor unit recruitment, motor unit synchronization, rate coding (i.e. firing frequency), and neuromuscular inhibition.

Motor unit recruitment affects a muscles ability to express force, with force production being related to the number and type of motor units recruited (Cormie et al., 2011a; Suchomel et al., 2018). It has been found that the ability to fully activate motor units involved in a given task affects the voluntary strength of the muscle (Miller et al., 1993). Motor units are recruited in a sequenced manner based on size (i.e. from small to large) and motor units are recruited based on

the magnitude of force and RFD required during a given task (Suchomel et al., 2018). This recruitment order has been found to be maintained during slow, graded, isometric, and ballistic actions (Suchomel et al., 2018). Despite the rapid nature of ballistic muscular contractions, the size principle of motor unit recruitment is maintained by the decrease in motor unit contraction thresholds and the increase in discharge rates when compared to slow-force contractions (Del Vecchio et al., 2018; Suchomel et al., 2018). In addition, the RFD has been identified as a critical aspect of dynamic muscle performance with research showing a link between the maximal strength of the muscle and its RFD (Inglis, McIntosh, & Gabriel, 2017). It is beneficial for an athlete to possess a higher peak RFD, as it has been found to be related to higher measures of lower body muscular strength in resistance training exercises (Wang et al., 2016). RFD may be determined by the ability to recruit larger motor neurons with greater and faster twitches, with the primary determinant of motor unit twitch force being the number of motor units innervated by the same axon (Del Vecchio et al., 2018).

The rate coding, or firing frequency, of a muscle also influences the ability of a muscle to express force, with the frequency at which α–motoneurons discharge action potentials to the motor units muscle fibres being a factor which can modify the muscles force production properties (Suchomel et al., 2018). Rate coding represents the rate of neural impulses transmitted from α–motoneurons to muscle fibres and can impact the ability of the muscle fibre to generate force in two ways: increasing action potential firing frequency enhances the magnitude of force generated during contractions, and the firing frequency impacts rate of force development and ultimately maximal force (Cormie et al., 2011a; Suchomel et al., 2018). RFD is associated to the neural drive (i.e. the ensemble of motor neuron action potentials that reach the muscle per unit time) during the very early phase (i.e. ~50ms) of muscular contraction (Del

Vecchio et al., 2018). Motor unit firing frequency plays a role in the development of Pmax by influencing the force and RFD of muscular contraction (Cormie et al., 2011a).

Motor unit synchronization has also been found to influence the ability of a muscle to express force (Suchomel et al., 2018). Motor unit synchronization occurs when two or more motor units are activated concurrently more frequently than expected for independent random processes, and is a measure of the correlated discharge of action potentials by motor units (Cormie et al., 2011a; Semmler, 2002). Motor unit synchronization may be more related RFD than to force production magnitude, however synchronization has commonly been suggested to augment force production and positively influence RFD (Cormie et al., 2011a; Suchomel et al., 2018).

Neuromuscular inhibition affects the ability of a muscle to express force (Suchomel et al., 2018). Neuromuscular inhibition refers to a reduction in neural drive because of neural feedback received from muscle and joint receptors that may negatively influence force expression (Suchomel et al., 2018).

1.2.5 Sex differences in neuromuscular performance. There are significant differences in the ability to express muscular force between males and females that have been well reported in the literature. Research has shown that males tend to be able to produce significantly higher amounts of strength and power than their female counterparts (Jones et al., 2016; Márquez, Alegre, Jaén, Martin-Casado, & Aguado, 2017; Rice et al., 2017). Various studies have reported a greater expression of Type-I muscle fibres in females versus greater Type-II fibre distribution in males (Rice et al., 2017). Males also tend produce higher amounts of absolute and relative values of strength in isometric strength testing procedures with males having been found to produce 1.30-1.34x the relative strength values as females (Jones et al., 2016). In addition to

having a superior ability to produce maximal force, males have been reported to produce 1.2x higher RFD in jumping tasks when compared to females which suggests that they can produce force faster than females (Alegre, Lara, Elvira, & Aguado, 2009; Laffaye, Wagner, & Tombleson, 2014; Márquez et al., 2017). These differences may be in part due to greater muscle CSA, muscle fibre size, muscle architecture, tendon length, and tendon stiffness (Márquez et al., 2017; Rice et al., 2017). Males have also been suggested to better take advantage of the SSC and can withstand greater stretch loads during jumping tasks which may contribute to superior jump height performance in males than females (Laffaye et al., 2014; Rice et al., 2017).

1.2.6 Effect of body size on muscular performance parameters. There are reports in the literature that body size confounds measures of performance parameters used for evaluating muscular force expression. Studies have shown that measures of maximal isometric strength and power are largely correlated with body mass and fat-free mass, with larger individuals producing greater measures of strength and power variables (Nikolaidis, Rosemann, & Knechtle, 2018). Scaling models as well as experimental data also suggest that muscular power increase with body size (Markovic, Mirkov, Nedeljkovic, & Jaric, 2014). It is also suggested that it is important to consider body mass when analyzing performance parameters of muscular testing, as body mass has been suggested to confound measures of strength and power performance (Markovic et al., 2014).

1.2.7 Training to address characteristics of neuromuscular performance. Strength training is a critical stimulus for inducing changes in muscular size, strength, and power (Jovanovic & Flanagan, 2014) and strength and conditioning professionals must develop training programs in order to maximize the desired characteristics of muscular strength. It is possible to affect change in the architectural and neurological factors that influence muscular force through

training.

Muscle CSA can be increased through strength training, with extensive research demonstrating that heavy strength training is an effective stimulus for eliciting a hypertrophic response in muscle (Cormie et al., 2011a). These increases in CSA are brought through an increase in the size and number of myofibrils within the muscle, occurring in both Type I and Type II muscle fibres as a result of chronic forceful muscular contractions (Cormie et al., 2011a; Miller et al., 1993). Training induced increases in CSA are typically accompanied by increases in maximal muscular strength and Pmax (Cormie et al., 2011a). It is thought that this improvement is due to an increase in cross-bridge interactions between actin and myosin within the myofibrils, and that contractile protein properties are shifted to a more economical cross-bridge cycling system through training (Cormie et al., 2011a; Suchomel et al., 2018).

Tendons can experience adaptations and significant architectural change from habitual loading achieved through training (G. McMahon, Morse, Winwood, Burden, & Onambélé, 2018; Oranchuk, Storey, Nelson, & Cronin, 2018). Region specific increases in tendon thickness and stiffness in response to resistance training optimize the time and magnitude of force transmission between muscle and bone with re-habilitative, pre-habilitative, and performance enhancing benefits (Oranchuk et al., 2018). It is suggested that increased tendon stiffness may be due to increased tendon CSA without any alteration in tendon viscoelastic properties, with the changes of the tendon-aponeurosis complex and free tendon stiffness possibly being dependent on the increase in the size of the tissues (Massey, Balshaw, Maden-Wilkinson, Tillin, & Folland, 2018; Oranchuk et al., 2018). Intensity of mechanical loading may also be of importance to achieve tendon adaptations (Massey et al., 2018; Oranchuk et al., 2018). Research has shown an increase in tendon stiffness with heavy resistance training and an increase of tendon elongation under

stress (i.e. an indication of elasticity) following low-intensity resistance training (Oranchuk et al., 2018). Plyometric exercises have also been shown to increase tendon stiffness and may provide a potent stimulus for increasing stiffness of the muscle-tendon complex (Kubo, Ishigaki, & Ikebukuro, 2017; Massey et al., 2018).

Resistance training is known to increase muscle fascicle pennation angle (Erskine, Fletcher, & Folland, 2014; Nóbrega, Ugrinowitsch, Pintanel, Barcelos, & Libardi, 2018; Timmins, Shield, Williams, Lorenzen, & Opar, 2016). Increases in pennation angle are common in hypertrophied pennate muscles as a result of resistance training protocols, and increases in muscle strength and muscle CSA may be followed by increases in muscle fiber pennation angle (Nóbrega et al., 2018; Vieira et al., 2018). It should be noted that there is a possibility for increases in pennation angle to be reliant on the extent of muscle fibre hypertrophy that occurs, with concurrent increases in fascicle length potentially countering the tendency for pennation angle to increase (Timmins et al., 2016).

Individuals who participate in strength training can develop greater levels of force when compared to untrained subjects with this difference being partly of neural origin and explained by training induced changes in the neural drive to muscles (Del Vecchio et al., 2018). Strength training increases motor unit recruitment which results in the preferential recruitment of high-threshold motor units, and lowering the thresholds of motor unit recruitment (Cormie et al., 2011a). These adaptations act to increase agonist activation during dynamic movements, resulting in increased agonist activation that results in increased tension development and consequently improved muscular strength and power production (Cormie et al., 2011a).

Strength training strategies including heavy resistance training and/or ballistic type movements may increase motor unit synchronization and force production (Suchomel et al.,

2018). Training related increases in RFD are associated with an increase in muscle activation at the onset of muscular contraction (Inglis et al., 2017) with chronic strength training involving explosive tasks resulting in faster recruitment of larger fast-twitch motor units (Del Vecchio et al., 2018). Faster motor unit recruitment increases the ballistic force capabilities of a muscle since the size of the motor unit determines the recruitment threshold and is associated with motor unit mechanical properties, and therefore it appears beneficial to recruit high-threshold motor units during training (Del Vecchio et al., 2018; Suchomel et al., 2018). Research has also shown that strength training may down-regulate 1b afferent feedback to spinal motoneurons and lead to reductions in neuromuscular inhibition (Suchomel et al., 2018). The maximal firing frequency of motoneurons can also be affected through strength training with an increase in firing frequency being associated with an increase in muscular force and power (Cormie et al., 2011a).

Different aspects of the F-v relationship can be addressed through strength training. As Pmax is determined by the parameters of the F-v relationship improvements in Pmax output can be achieved by increasing maximal force, increasing maximal velocity, and/or decreasing the degree of the power curve (Cormie et al., 2011a; Pierre Samozino et al., 2017). The velocity at which a movement is trained should be considered to address specific adaptations to the F-v relationship, as there is a velocity-specific response to training with some improvement made slightly above and slightly below the actual training velocity of an exercise (Cormie et al., 2011b).

1.2.8 Exercise selection for athletic training. As the ability to generate Pmax in sport is dependent on the nature of movements involved, the exercises that are selected for a training program may influence the magnitude of observed performance improvements and adaptations (Cormie et al., 2011b). Traditional resistance training exercises (e.g. press, back squat,

horizontal row) have a period where the load is decelerated towards the end of the range of motion (Cormie et al., 2011b). This deceleration is associated with decreased agonist muscle activation and potentially increased muscle activity in antagonist muscles to stop the load at the end of the range of motion, which may reduce training effect for power development (Cormie et al., 2011b). Improvements in power development through traditional resistance training exercises have primarily been a result of physiological adaptations that are responsible for increasing maximal strength (i.e. increasing cross-sectional area and neural drive to the muscle) (Cormie et al., 2011b).

Alternatively, ballistic exercises circumvent any deceleration phase by requiring the athlete to accelerate throughout the entire range of motion to the point of projection (i.e. point of release) and do not have the limitations associated with traditional resistance training exercises (Cormie et al., 2011b). Use of ballistic exercise in power training programs is effective at enhancing Pmax in sport-specific movements and power production capabilities under a variety of loading conditions (Cormie et al., 2011b). A wide spectrum of loading conditions have been reported useful for training Pmax output in ballistic exercises, with the nature of the exercise being important to consider when selecting training load (Cormie et al., 2011b).

Plyometric exercises, characterized by rapid SSC muscle actions performed with little to no external resistance, are popular when training for Pmax and athletic performance (Cormie et al., 2011b). These exercises can be performed with specificity to upper and lower body muscle groups with exercise examples including a variety of unilateral and bilateral medicine ball throws, bounds, push-ups, hops, and jumping variations (Cormie et al., 2011b). Overload for plyometric exercises is applied by increasing the stretch rate by minimizing the duration of the stretch shortening cycle and/or stretch load (e.g. by increasing the height of the drop during a

drop jump) (Cormie et al., 2011b). These exercises can be tailored to train SSC movements across a variety of time demands including short (100-250ms) or long (>250 ms) movements in an attempt to reflect sport-specific activities (e.g. ground contact in sprinting is a short movement, whereas a throw is a long movement) (Cormie et al., 2011b). Since these exercises can be tailored to target a variety of sport-specific movements, inclusion of plyometric exercises in power training programs has been found to enhance Pmax by eliciting specific adaptations including increasing firing frequency and intermuscular control resulting in improved RFD capacity (Cormie et al., 2011b).

Weightlifting exercises (e.g. clean and jerk and snatch) are commonly incorporated into training programs for competitive athletes (Cormie et al., 2011b). These exercises require acceleration through the entire propulsive phase (i.e. the second pull) which causes projection of the barbell, and often the body, into the air through movement patterns that are generally believed to be very similar to athletic movements common to many sports such as jumping and sprinting (Cormie et al., 2011b). A major difference between weightlifting exercises and plyometric exercises is that they require active deceleration of the body mass in order to catch the barbell, which is inherent for the high force and velocity nature of weightlifting exercises and creates the potential for these exercises to produce large power outputs across a variety of loading conditions (Cormie et al., 2011b). Coupled with the specificity of their movement patterns to numerous athletic movements, the high force and velocity nature of weightlifting exercises creates the potential for them to be very effective power training exercises (Cormie et al., 2011b).

Load specificity should be considered when designing training programs to increase maximal force expression. Pmax during a movement is dependent on the type of movement as well as the

load applied to the movement, and a range of loading conditions have been considered to elicit improvements in Pmax including heavy loads, light loads, the 'optimal' load, and a combination of loads (Cormie et al., 2011b). Training with heavy loads is commonly prescribed to improve muscular strength and is commonly used in power training programs incorporating ballistic and/or weightlifting exercises (Cormie et al., 2011b). Because of the relationship between maximal strength and Pmax, the use of heavy loads in training may increase maximal strength and subsequently the ability to produce Pmax. In addition, the Type II muscle fibres that are predominantly responsible for powerful athletic performance are more fully recruited and therefore trained when training involves the use of heavy loads (Cormie et al., 2011b). Training with light loads in conjunction with ballistic and/or plyometric exercises is commonly recommended and utilized in athletic training due to the fact that it allows athletes to train at velocities that are similar to those encountered in actual on-field sport-specific movements (Cormie et al., 2011b). The 'optimal' load (i.e. the load that elicits Pmax production in a specific movement) provides an effective stimulus for eliciting increases in maximal power as improvements in power are most pronounced at the load used in training (Cormie et al., 2011b). This is maximized at a variety of loading ranges depending on the exercise as power output is influenced by the nature of the movement because of the differences in the load that must be projected (i.e. jump squats involve the athletes bodyweight plus additional load, whereas weightlifting exercises exclude the athletes bodyweight) (Cormie et al., 2011b). Training with a combination of loads allows the targeting of all areas of the F-v relationship with the intention of developing adaptations in muscular power output throughout the entire curve (Cormie et al., 2011b). Training with light loads has been shown to improve performance in the high-velocity

area of the F-v curve, and the use of heavy loads enhances performance in the high-force area of the F-v curve (Cormie et al., 2011b).

Velocity specificity should be considered when training with the intent of increasing maximal muscular force and maximal contraction velocity. It has been suggested that adaptations following training are maximized at or near the velocity of the movement used during training and as such the actual movement velocity is critical because of a velocity-specific response to training (Cormie et al., 2011b). It should be noted that some changes in force and power production have been found just above and below the specific velocity encountered in training suggesting that training elicits some velocity-specific adaptations that can transfer to athletic performance, however the mechanisms that are responsible for this effect are currently unknown (Cormie et al., 2011b).

Research has shown that individualized training programs are more effective than general training programs when addressing specific aspects of an athletes sport performance. Individualized training programs have been reported to have a higher impact on specific task performance (e.g. jumping performance) than programs that are designed generically (Jiménez-Reyes, Samozino, Brughelli, & Morin, 2016). In order to maximize athletic performance over a career, long-term training strategies should be implemented to promote the greatest muscular strength within the context of each sport or event (Suchomel et al., 2016). Individualization of training is important as it appears that there is a sequence of training that elicits the greatest benefits from resistance training which is ordered as increasing muscular cross-sectional area, increasing work capacity (i.e. force production capacity), and is then follows by a phasic progression that can produce superior strength-power gains (Suchomel et al., 2018). Periodization is endorsed and used frequently to maximize the long-term improvements in

strength (Cormie et al., 2011b). Integration of various strength and power training techniques are used to elicit superior long-term improvements in maximal strength, power, and sport performance (Cormie et al., 2011b).

It should be noted that the magnitude of potential adaptation (i.e. the window of adaptation to training) is heavily influenced by the specific neuromuscular characteristics of each individual, and the window of adaptation to training should be considered when individualizing training programs (Cormie et al., 2011b; Suchomel et al., 2018). These neuromuscular characteristics include genetics, slow velocity strength, high velocity strength, RFD, SSC capability, intramuscular coordination, intermuscular coordination, and skill (Cormie et al., 2011b; Suchomel et al., 2018). As such, training program design should target the components of maximal muscular force expression with the greatest window of adaptation for each athlete (Cormie et al., 2011b).

1.2.9 Strength profiling in athletes. Establishing a means of measuring muscular force expression is an essential component of monitoring the effectiveness of strength training programs (Jiménez-Reyes, Samozino, Brughelli, & Morin, 2017; Thomas, Jones, & Comfort, 2015)**.** Testing protocols should consider the biomechanical characteristics (e.g. maximal force, RFD, velocity) when developing test protocols that help to guide assessment, monitor training progress, and inform decisions regarding the optimization of training to maximize sport performance (Brady et al., 2018; Thomas, Jones, & Comfort, 2015).

The direct method of strength assessment is used because it is an effective means of evaluating dynamic muscular performance. The most common measure of an athlete's maximal strength is the performance of a 1-repetition maximum (1RM) test, where an exercise is performed only once with the heaviest possible load (Suchomel et al., 2016). Performance in

1RM testing may be relevant to an athlete's performance due to similarities between the movements performed during the exercise and movements performed in various sports and events (Suchomel et al., 2016). The direct method of measuring an athlete's maximal strength is useful for programming as the relative percentages of the 1RM are usually prescribed as training intensity in resistance training programs (Suchomel et al., 2016). The 1RM can also be accurately predicted by the use of a repetition-to-failure method with a submaximal load and inputting these variables (i.e. weight lifted, number of repetitions) into predictive mathematical equations (Bazuelo-Ruiz et al., 2015; Jidovtseff, Harris, Crielaard, & Cronin, 2011). Despite the popularity of the direct method several issues with its evaluation have been noted including an increased chance of muscle pain or injury related to muscle tension and unstable posture in inexperienced athletes as well as impracticality in large groups (Bazuelo-Ruiz et al., 2015; Jovanovic & Flanagan, 2014; Picerno et al., 2016). Additionally, the direct method may be problematic for certain populations including youth athletes (Jidovtseff et al., 2011). The emphasis on avoidance of direct 1RM evaluation has driven the need for less invasive means of evaluating strength characteristics, and with the advent of long-term athlete development and the earlier specialization of athletes it may be appropriate for practitioners to investigate less invasive means of identifying strength characteristics (McKay et al., 2016).

In order to understand the kinetic and kinematic properties of dynamic muscular performance practitioners have investigated the use of specialized tools. Measurements of force on force platforms, considered the gold standard of force data collection, have become popular among strength and conditioning practitioners (Cronin et al., 2004; Dos'Santos, Thomas, Comfort, McMahon, Jones, et al., 2017; García-Ramos et al., 2015; Jiménez-Reyes, Samozino, Pareja-Blanco, et al., 2017). These force platforms are used to assess the neuromuscular capabilities of

athletes and to enable the measurement of many kinetic and kinematic variables including force and velocity (Jiménez-Reyes, Samozino, Pareja-Blanco, et al., 2017). Despite their usefulness there are some issues associated with force platforms such as their relative immobility, as these devices can be sensitive to extraneous vibration when not properly mounted which limits their assessment to laboratory settings (Cronin et al., 2004; García-Ramos et al., 2015). Additionally, the high cost of these devices and their accompanying electronic equipment may also place them outside of the budget for many strength and conditioning facilities (Cronin et al., 2004; García-Ramos et al., 2015). The cost of these devices has caused a proliferation in the market of less expensive and more versatile equipment to collect kinetic and kinematic information similar to the force platform but with more practicality in field settings (Cronin et al., 2004; García-Ramos et al., 2015).

Linear position transducers have the advantage of low cost, simplicity of use, versatility, and ease of transport when compared to force platforms (García-Ramos et al., 2015). These devices are typically embodied as a central processing unit that attaches to resistance training equipment via a retractable measuring cable that confers physical attributes (i.e. the length of the cable) into electrical signals that yield the displacement of the object (García-Ramos et al., 2015; Jovanovic & Flanagan, 2014). Linear position transducers are composed of four main parts: a measuring cable, spool, spring, and a rotational sensor (Harris, Cronin, Taylor, Boris, & Sheppard, 2010). Inside of a housing component a stainless steel cable is wound on a cylindrical spool that is machined to have a constant diameter as it turns and the measuring cable unreels (Harris et al., 2010). To maintain cable tension, a spring is coupled with the spool, and the spool is coupled to the shaft of a rotational sensor (Harris et al., 2010). As the cable extends through the movement it causes rotation of the spool and sensor shaft, which creates an electrical signal that is

proportional to the cable's linear extension or velocity (Harris et al., 2010). When evaluating movements that are typical in a weight-room setting (e.g. bench press, back squat, Olympic lift variations) it is suggested that the minimal sampling rate of a linear position transducer should be 200 Hz, with a sampling frequency of 500-1000 Hz being desirable (Harris et al., 2010). It should be noted that with earlier devices horizontal displacement greatly influenced measurements, but more recently linear position transducers have become available that incorporate a sensor near the bottom of the retractable cable that enables measurement of the angle of the cable leaving the spool (Harris et al., 2010; Wadhi, Rauch, Tamulevicius, Andersen, & De Souza, 2018). This allows vertical displacement to be accurately measured through correcting for any horizontal movements through trigonometry, and enables the devices to be useful for movements with components that occur outside of the vertical plane (e.g. most weightlifting movements) (Harris et al., 2010). Without this correction, linear position transducers measure higher movement distance, and as such report higher measurement parameters (Wadhi et al., 2018). Temperature can also affect the accuracy of the output of linear position transducers, with changes in temperature potentially causing changes in the measured parameter (Harris et al., 2010).

Studies have shown good relationships between linear position transducers and force platforms in their measurements of peak and mean force ($r=0.94–0.99$, $r=0.96–0.99$; $p<0.001$, respectively), peak and mean velocity ($r=0.83–0.91$, $r=0.87–0.89$; $p<0.001$, respectively), and peak and mean power ($r=0.90–0.94$, $r=0.93–0.96$; $p<0.001$, respectively) (García-Ramos et al., 2015, 2016). In particular, GymAware linear position transducers have been shown to be valid for accurately measuring peak velocity during resistance training movements (Wadhi et al., 2018). Research has shown that measurements of power tend to be less reliable than velocity

measurements, and can be over-exaggerated when compared to measurements obtained via optic measurement (Harris et al., 2010). With this said, linear position transducers have a moderate to high test-retest reliability (ICC=0.922-0.988, CV=9.6-13.2%, CI=95%) when measuring peak power and peak velocity when using different loads in various resistance training exercises (e.g. back squat, bench press, free weight biceps curls) (Bosquet et al., 2010; Garnacho-Castaño et al., 2015).

The use of these tools has allowed strength and conditioning practitioners to evaluate muscle force expression capabilities in different types of muscular contraction across a range of force and velocity specific demands.

Isometric strength has been found to show relationships with dynamic performance characteristics including 1RM tests, acceleration ability, and vertical jump ability (Brady et al., 2018; Dos'Santos, Thomas, Comfort, McMahon, Jones, et al., 2017; McGuigan & Winchester, 2008; McGuigan et al., 2006; Thomas, Jones, & Comfort, 2015; Wang et al., 2016). The relationships between isometric strength and dynamic performance have been established in various athletic populations including multisport collegiate athletes, professional rugby league players, sprint cyclists, golfers, female volleyball players, and weightlifters (Dos'Santos, Thomas, Comfort, McMahon, Jones, et al., 2017). These isometric tests have been used to evaluate the different phases of an exercise, the effect of training programs on muscular force expression characteristics, and to determine the force production differences among athletes (Suchomel et al., 2016).

One popular isometric test to measure peak force values is the performance of a maximal effort isometric mid-thigh pull (IMTP) (Brady et al., 2018; Thomas et al., 2017). The IMTP is a closed-chain, multi-joint isometric assessment that is performed at specific joint angles to

measure an individuals' maximum force-generating capacity and RFD capacity (Brady et al., 2018). The IMTP peak force has shown high reliability (ICC ≥ 0.89, CV ≤ 7.9%) within and between sessions and has shown strong associations with 1RM back squat, power lean, deadlift, and weightlifting performance (Dos'Santos, Thomas, Comfort, McMahon, & Jones, 2017). Joint angles for this test differ across studies with knee angles between 120-150 degrees and hip flexion angles ranging from 124-175 degrees (Brady et al., 2018), with this lack of consistency potentially causing issues regarding the comparison of normative IMTP data (Brady et al., 2018). Performance of an IMTP test is also relatively timely when compared to the direct method of 1RM determination, making it advantageous to employ in group settings (Suchomel et al., 2016).

The IMTP test is modelled off of the second pull position in Olympic weightlifting movements as it is the strongest and most powerful position during weightlifting movements, generating the highest forces and velocities during any part of the lift (Brady et al., 2018). The test is typically performed by the subjects self-selecting hip and knee joint angles to resemble the second pull of a power clean and performing a maximal isometric contraction by attempting to extend the legs for a pre-determined sampling window (Dos'Santos, Thomas, Comfort, McMahon, Jones, et al., 2017). Research has shown that sampling frequencies of 500-1000 Hz have been highly reliable within sessions (ICC=0.84-0.98, CV=4.05-10.00%) and between sessions (ICC=0.86-0.96, CV=3.76-7.87%) for the measurement of force-time variables of isometric contractions (Dos'Santos, Thomas, Comfort, McMahon, Jones, et al., 2017; García-Ramos et al., 2015, 2016; Thomas, Jones, & Comfort, 2015). A single study has investigated the optimal position for the IMTP and found that a knee angle between 130-140 degrees and an upright trunk position of around 145 degrees of hip flexion is likely optimal for performance (Brady et al., 2018). It is important that the joint angles used should be consistent between

trials/testing sessions/studies to ensure a consistent length-tension relationship of involved muscle groups, as according to the length-tension relationship the muscles display different levels of maximal isometric force production depending on the length at which it is tested (Brady et al., 2018).

Ballistic peak force is often measured through the performance of a squat jump (SJ) or countermovement jump (CMJ) performed on a force platform (Comfort et al., 2017). These jumps are commonly used to monitor neuromuscular function (Thomas et al., 2017). In a standing vertical jump, a countermovement is a preliminary downward movement that flexes the hips and knees before shortening the muscle in an upward motion and generally produces higher vertical jump results (i.e. 5-10% higher) than without any countermovement (Jiménez-Reyes et al., 2014; Kim, Park, & Choi, 2014). The mechanisms responsible for this increase in height in terms of kinematics and muscle physiology have been discussed in the literature (Kim et al., 2014). The pre-stretch before muscle shortening during the upwards action may allow the muscle to build to a high active state which results in greater joint moments at the start of push-off (Kim et al., 2014). It is also suggested that the countermovement enables the storage of elastic energy and reutilization in the muscle and/or tendons non-contractile tissue to provide extra work (Cormie et al., 2011a; Kalkhoven & Watsford, 2018; Kim et al., 2014; Suchomel et al., 2018). It has been reported that higher jumps require a larger countermovement and forward inclination of the trunk and, in conjunction with the swing of the arms, result in greater height of the centre of mass at take-off than jumps with smaller countermovement (A. S. Salles, Baltzopoulos, & Rittweger, 2011). Peak vertical displacement is resultant of vertical velocity in conjunction with the height of the centre of mass at toe-off, with vertical velocity being determined by vertical impulse (i.e. force integrated over the time of the concentric range of

motion) (Haug et al., 2015). Performance in any jump is related to the impulse produced, and the use of the countermovement likely allows the jumper to increase their mechanical impulse at the beginning and throughout the push-off phase of the jump (Jiménez-Reyes et al., 2014). It should be noted that in order to apply the required impulse for a relatively higher jump there is a larger peak ground reaction force applied throughout the movement (A. S. Salles et al., 2011).

Measures of both SJ and CMJ peak force have been found to be highly reliable with low variability (ICC=0.952-0.987, CV=2.01-4.60%) (Comfort et al., 2017). When measuring jump performance increasing the number of trials may potentially overcome the variability that is intrinsic in all human movement, however it should be recognized that it may be impractical or physically impossible to collect multiple trials in certain situations (Kennedy & Drake, 2018). It has been suggested that it may be preferential to take the mean value of two to three trials instead of taking the values of the best trial when assessing jump performance (Kennedy & Drake, 2018).

Linear position transducers allow the measurement of the velocity characteristics of muscular contraction and can be used to establish an exercise specific F-v profile (Bosquet et al., 2010; García-Ramos et al., 2016; Jovanovic & Flanagan, 2014). By measuring the velocity characteristics of loaded ballistic exercises the exercise F-v profile represents the dynamic capability of the neuromuscular system to function under various loading conditions and has significant implications in movement performance (Cronin et al., 2003; Jovanovic & Flanagan, 2014; Mundy et al., 2016). It has been shown that the velocity at which a given lift is performed is related to the F-v relationship of each athlete, as well as the current state of neuromuscular fatigue (Dorrell, Moore, Smith, & Gee, 2018). The understanding of the F-v relationship makes it possible for practitioners to produce an exercise-specific F-v profile that allows one value to

predict the other (Jovanovic & Flanagan, 2014). The strength of the exercise-specific F-v profile has been found to be high and comparable to the direct method of 1RM for evaluating force-production capability (Zivkovic et al., 2017). The use of the exercise F-v profile allows selective assessment of force, velocity, and power generating capacity of muscles performing functional movements that cannot be assessed from a single movement condition as it typically applied in routine testing procedures (Zivkovic et al., 2017). The two independent parameters of the exercise F-v profile are the slope (α) and the F-v intercept (F_0), which is interpreted as measures of strength across various loading conditions (Jovanovic & Flanagan, 2014). Both peak concentric velocity and mean concentric velocity have been used in the identification of the exercise F-v profile (Zivkovic et al., 2017). When measuring non-ballistic strength training exercises (e.g. bench press, back squat) it has been suggested that practitioners input mean concentric velocity as a means of estimation as it is thought to better represent the ability of the athlete to move the load through the entire concentric phase of the movement (Jovanovic & Flanagan, 2014). It has been noted that mean concentric velocity values are highly influenced by arbitrary decisions regarding determination of the exact start and end points of the concentric phase of the movement (García-Ramos et al., 2016). Specifically, when referring to ballistic exercises (e.g. SJ, CMJ) some authors recommend the selection of peak concentric velocity values rather than mean concentric velocity values (García-Ramos et al., 2016). When observed from peak force and velocity values the F-v relationship reveals a higher maximal velocity (V_0) than when observed from the mean force and velocity values, while F_0 remains similar (Jaric, 2015).

1.2.10 Applications for strength training programming. The use of these measuring tools has allowed strength and conditioning practitioners to selectively assess aspects of muscular

force expression and use that information to guide training programming to address perceived deficiencies in factors of athletic performance.

The comparison of isometric and concentric muscular contraction has been used to guide training programming. The evaluation of the relationship between ballistic peak force capabilities and isometric peak force capabilities is referred to in the literature as the Dynamic Strength Index (DSI) (Comfort et al., 2017; Thomas, Jones, & Comfort, 2015). The DSI is expressed as a ratio of ballistic peak force : isometric peak force, and allows comparison of an athletes peak ballistic force capabilities to their peak isometric force capabilities (Comfort et al., 2017; Thomas, Jones, & Comfort, 2015). The DSI typically yields high reliability (ICC of ≥0.92) and low variability (CV of ≤4.6% (J. J. McMahon, Jones, Dos'Santos, & Comfort, 2017). The use of several isometric contraction tests has been explored, and the IMTP has become a common means of assessing maximum isometric force capability for the DSI (Comfort et al., 2017; Thomas, Jones, & Comfort, 2015). Both the SJ and CMJ have been used to measure ballistic force capabilities for the DSI, with the DSI-CMJ being more consistent (ICC=0.920-0.952, CV=3.8-4.57%) than the SJ-DSI (ICC=0.419-0.948, CV=4.03-15.91%) due to potential learning effects, and that the peak force during the propulsive phase of the CMJ is more reliable and less variable when compared to that the of the SJ (Comfort et al., 2017). While the SJ is easier to standardize it is still difficult to prevent small amplitude countermovement's from occurring prior to the propulsive phase of the jump (J. J. McMahon et al., 2017). Allowing athletes to select their preferred countermovement amplitude (i.e. depth) with the instruction to jump as fast and high as possible has been enforced in studies which have calculated the DSI using the CMJ (J. J. McMahon et al., 2017). It should be noted that jump strategy, and not just strength, affects the peak force during the propulsive phase of the jump (J. J. McMahon et al.,

2017). Countermovement magnitude positively affects jump height through application of a net impulse characterized by longer time of force application, positively affects peak joint (i.e. ankle, knee, hip) torques and is negatively related to peak ground reaction force with little to no bearing on peak jump power (J. J. McMahon et al., 2017; A. S. Salles et al., 2011). Performance in both of these exercises (i.e. SJ and CMJ) has been shown to relate to sport-specific dynamic tasks (e.g. sprinting, jumping, and change of direction performance (Thomas et al., 2017).

Loaded ballistic exercises (e.g. SJ and CMJ) have been commonly used to identify the lower-body exercise F-v profile of an athlete (Jovanovic & Flanagan, 2014). To accomplish this the athlete performs the ballistic exercise with an Olympic barbell loaded with weight plates placed around the posterior aspects of the shoulder, and the kinematic properties of that exercise are measured (Jovanovic & Flanagan, 2014; Mundy, Smith, Lauder, & Lake, 2017). Both maximum and average data across trials can be used to obtain the exercise F-v profile, with the CMJ providing a stronger F-v relationship than the SJ in both cases (Cuk et al., 2014). Both absolute loads and loads relative to the 1RM have been explored, with a minimum of 4-6 loading conditions and a decline in velocity of at least 0.5 m/s across all loading conditions being essential for accurate measurement of the exercise F-v profile (García-Ramos et al., 2017, 2015; Jidovtseff et al., 2011; Jovanovic & Flanagan, 2014). The effects of barbell loading on CMJ performance are well reported, with a decline in velocity reported as the barbell load increases (Mundy et al., 2017). While originally investigated with the ballistic exercise being performed inside a Smith machine, recent research has investigated this relationship with free weight exercises (García-Ramos et al., 2017). This research has shown a strong linearity of the relationship with the CMJ over SJ (Fisher's $Z=2.06\pm0.21$ and 1.92 ± 0.21, respectively), free over Smith loading type (Fisher's $Z=2.06\pm0.18$ and 1.92 ± 0.19, respectively), and maximum over

averaged variables (Fisher's Z=2.08±0.16 and 1.90±0.19, respectively) as well as high reliability of its parameters regardless of jump type (i.e. SJ or CMJ) (CV ratios=1.25-1.79, 95% CI) , loading type (i.e. free weight or Smith machine) (CV ratios=1.12-1.36, 95% CI), or type of outcome variables (i.e. averaged or maximal across trials) (CV ratios = 1.17-1.31, 95% CI) (García-Ramos et al., 2017). Because of the stronger linearity of the F-v relationship and the higher reliability of the F-v parameters is has been recommended to use the CMJ over the SJ, free weights over the Smith machine, and peak over mean velocity values when assessing a ballistic lower-body exercise F-v profile (Banyard et al., 2017; García-Ramos et al., 2017; Jiménez-Reyes, Samozino, Pareja-Blanco, et al., 2017).

The results of both the DSI and the exercise F-v profile can be used to guide the direction of strength training programming to favour more ballistic or more maximal strength based exercise and load selection (Jiménez-Reyes, Samozino, Pareja-Blanco, et al., 2017; Sheppard et al., 2008; Thomas, Jones, & Comfort, 2015). Programs can favour ballistic movements or maximal strength exercise in an attempt to maximize the desired variables of athletic performance (Jiménez-Reyes, Samozino, Pareja-Blanco, et al., 2017; P. Samozino et al., 2014; Sheppard et al., 2008; Thomas, Jones, & Comfort, 2015). When using the DSI to guide training programming, recommendations for interpreting the ratio suggest focusing on ballistic force production when the ratio is low (e.g. <0.6) and placing a focus on strength development when the ratio is high (e.g. >0.8) (Comfort et al., 2017; Thomas, Jones, & Comfort, 2015). When interpreting the DSI relative force capacity must still be considered because if an athlete is relatively weak they can greatly benefit from increasing their maximal strength (J. J. McMahon et al., 2017). When using the exercise F-v profile to guide training, if the velocity of the exercise is 'poor' as additional load is added the practitioner can emphasize heavy load strength training

and high load power training (Jovanovic & Flanagan, 2014; Sheppard et al., 2008). Whether the velocity performance is 'poor' can be determined by the slope of the exercise F-v profile (P. Samozino et al., 2014; Pierre Samozino, Rejc, Di Prampero, Belli, & Morin, 2012). An exercise F-v profile in which the velocity of lighter loading conditions is relatively low compared to heavier maximal loading conditions could be considered poor (Jovanovic & Flanagan, 2014), being indicated by less variability in the velocities attained with the different loading conditions. It is worth noting that while all parameters of the F-v relationship have been reported to have high reliability the value of α (i.e. the slope) has the most variability between subjects, and this is likely due to individual differences in the ability to generate ballistic strength (García-Ramos et al., 2017).

1.3 Future directions for research

With the increased specificity of training it is important for strength and conditioning practitioners to be able to effectively monitor performance variables to effectively guide specific strength training programming. These techniques have evolved from maximal strength evaluations using the direct method of 1RM establishment to indirect methods using technologies such as force platforms and linear position transducers. The indirect methods of strength performance measurement have been shown to be valid and reliable, as well as related to numerous components of dynamic athletic performance.

In addition to measurement of maximal force capabilities, various components of ballistic strength have become an area of interest for practitioners due to increased understanding of sport-specific demands. The evaluation of these characteristics has led to the development of several techniques including the establishment of the DSI and the individual F-v exercise profile. Both of these techniques have been found to be valid and reliable through use of different testing

methodologies, including the DSI established by the peak force values of CMJ : IMTP, and the loaded free weight CMJ completed with a series of absolute loads. The information provided by both of these techniques can be used to guide individual programming towards development of ballistic or maximal strength characteristics. The establishment of the DSI is less practical than the F-v profile due to the restrictive nature of the technology essential in its testing procedure. While the F-v profile can be accurately and reliably established using a linear position transducer by measuring peak concentric contraction velocity across a series of loading conditions, there are some characteristics of individual variability that affect that slope parameter used in its evaluation.

Research should be conducted in an attempt to identify the factors of F-v profile slope that could have an influence on its variability. The DSI provides a numeric value that represents the ratio of force an athlete is capable of generating in ballistic movements compared to their maximal force production value. Understanding this value allows exercise professionals guidance regarding whether to program for more ballistic or strength based activities. Exercise professionals derive the same guidance from examining the slope of the F-v profile. Given that the slope of the F-v profile is used for the same purpose in training as the numeric value of the DSI, it is possible that these two values are related.

1.4 Statement of the problem

There is a need to determine whether the slope of the F-v lower body profile is correlated to values of the DSI reported in the literature that are suggested to guide exercise professionals regarding emphasis on maximal strength or ballistic characteristic development. The purpose of this study is to evaluate whether the numeric value of the DSI is related to the value that

represents the slope of the F-v relationship established while performing a loaded free-weight CMJ.

1.5 Hypotheses

1.5.1 Primary hypothesis. It is hypothesized that the values of the DSI that are recommended for focus on development of ballistic characteristics are correlated to the slope of a F-v lower body profile that displays relatively low velocity characteristics at submaximal loads, and vice versa.

1.5.2 Secondary hypothesis. It is hypothesized that measures of isometric and ballistic peak force will be correlated with peak propulsive velocity performance across a series of loaded CMJ conditions.

CHAPTER 2 – METHODS

2.1 Experimental Design

The current study used a cross-sectional correlational design. Prior to participation in the study all participants were required to complete the Get Active Questionnaire, which screens for potential health limitations that could preclude participation in the study (see Appendix A). Participants were asked to come to the testing centre (High Performance Training Centre, 160 Active Living Centre, University of Manitoba) on two occasions at their convenience, first to perform a brief familiarization session of the testing protocols and a subsequent session to perform approximately 1.5 hours of testing. During the familiarization session demographic and anthropometric information was collected and participants were evaluated using the Landing Error Scoring System Real-Time (LESS RT). Both sessions began with a standardized warm-up routine consisting of 5 minutes of cycling followed by a standardized warm-up specific to the testing protocols consisting of multiple sets and reps of the CMJ and the back squat at different loads (McGowan, Pyne, Thompson, & Rattray, 2015). For specific details of this warmup, refer to Appendix B. Pending successful completion of the LESS RT during the familiarization session participants were then introduced to the F-v profile and DSI testing procedures. For the familiarization session participants performed single sub-maximal effort attempts of the protocols of DSI evaluation and lower body Force-velocity profile evaluation. For the data collection session, participants performed 5 minutes of cycling followed by the test-specific warmup described in Appendix B. The data collection session followed the full testing protocol at maximal effort to determine the DSI from the CMJ PF/IMTP PF and the lower body F-v profile from a series of unloaded and loaded CMJ's. The order of the testing protocols was randomly determined, with 5 minutes of rest given between testing protocols to limit fatigue. All

participants were subjected to the same testing protocols regardless of demographic. The peak force values necessary for interpretation of the DSI were measured on a force platform and exported to a customized Excel spreadsheet for analysis. The peak velocity values necessary for the lower body F-v profile were measured by a linear position transducer and inputted into a customized Excel spreadsheet for analysis. The results of both the DSI and lower body F-v profile evaluation were then analyzed using statistical software. All measurements for the present study were performed by the present author.

2.2 Participants

106 participants were initially recruited for the study; n = 17 were unresponsive after initially agreeing to participate, and n = 3 failed the LESS-RT test which was an exclusion criteria for study participation. This left 86 participants who completed all the data collection procedures. Participants from this study were primarily a convenience sample selected from the Varsity athlete pool at the University of Manitoba. Participants were also recruited from outside of the pool of Varsity athletes at the University of Manitoba. Recruitment for this study was accomplished through recruitment posters, social media, and word of mouth. Sample size for this study was determined according to sample size calculation formula $n = (n_0 - b)\,(\omega_0/\omega)^2 + b$ and referring to Table 1 as described by (Bonett & Wright, 2000). Both males and females were recruited for this study. All participants for this study were 18 years of age or older. All participants for this study had at least 2 consecutive months of regular weight training (2 times per week minimum) prior to participation in the study and had no injuries or conditions that would prevent them from participation in resistance exercise. Following a verbal and written explanation of the procedures and potential risks participants provided their written informed

consent. The study was approved in accordance with the University of Manitoba Research Ethics Board for research involving human participants.

2.3 Equipment

2.3.1 Anthropometric assessment. In order to assess participant height a Charder Wall-Mounted Stadiometer – HM230M ("Wall-Mounted Stadiometer—HM230M," n.d.) was used. In order to assess leg length and thigh girth a Medline anthropometric measuring tape was used.

2.3.2 Dynamic Strength Index assessment. Participants performed the CMJ and IMTP tests on a Quattro jump performance analysis system force platform (Quattro Jump type 9290CD, Kistler, USA, Amherst, NY, USA), with data being processed via a laptop computer connected to the force platform running Quattro Jump Type 2822A101 Version 1.1.0.3 software. The CMJ was performed in an akimbo position on the force platform. The participants pulled on a customized mounted IMTP bracket that is set into the base structure of the force platform that is capable of being adjusted vertically in 2.5 cm increments to perform the IMTP test. Standard lifting straps were used to attach the participant's hands to the bar to ensure that they did not lose grip of the bar during the IMTP test.

2.3.3 Lower body Force-velocity profile assessment. Participants performed the lower body F-v profile assessment with DHS standard Olympic barbells (15 or 20kg) loaded with DHS brand Olympic bumper plates (sizes of 0.5kg, 1kg, 1.5kg, 2kg, 2.5kg, 5kg, 10kg, 15kg, 20kg, and 25kg). Body mass for the lower-body F-velocity profile was evaluated using a digital scale (KiloTech KWS VS2000, Kilotech Inc., Canada, Lachine, QC, Canada). Peak velocity data during the CMJ trials was captured with a GymAware PowerTool5 (Kinetic Performance Technology Pty. Ltd., 8/26-28 Winchcombe Ct, Canberra ACT 2602). Recording sheets were

used to write down peak velocity during the testing session, which was then transcribed into a customized Excel spreadsheet.

2.4 Procedures

2.4.1 Demographic assessment. Participants were asked to fill out a recording sheet in order to answer a short series of questions asking about date of birth, biological sex, primary sport that participants identify with, highest level of sport participation, years of sport participation, and years of resistance training.

2.4.2 Anthropometric assessment Height was measured using a stadiometer, with the head in an anatomically neutral position, feet directly underneath the hips, and without footwear. Leg length was assessed using a tape measure and was measured on each leg from the anterior superior iliac spine (ASIS) to the inferior aspect of the heel. Thigh girth was assessed by measuring the mid-point of the thigh between ASIS and the upper pole of the patella and using a tape measure to assess thigh circumference at this point (Cooper, Dodds, Adams, DeDombal, & Steele, 1981). Measurements were taken to the nearest 0.25cm.

2.4.3 LESS RT. Following a general cycle ergometer warm-up, participants were screened for movement deficiencies and increased likelihood of injury during exercise by the Landing Error Scoring System Real-Time (LESS RT) test. If a participant scored 5 or greater during the testing session they were excluded from continued participation in the rest of the study, as scores of 5 or greater have been found to be related to higher incidences of injury during exercise ("Landing Error Scoring System (LESS)," 2017). In order to complete the LESS-RT, participants performed 4 trials of a standardized jump landing task that required them to jump forward from a 30cm high box (placed 50% of the distance of their height away from a

target landing area), land in the target landing area, and immediately rebound by jumping to a maximal vertical height on landing (Padua et al., 2011). During instruction for this task, emphasis was placed on participants starting the jump in neutral position and each jump was considered successful if both feet simultaneously left the box without large upward motion after takeoff from the box, landing in the target landing area, and completing the task in a fluid motion with no pause in the body's centre of mass after making contact with the ground until takeoff of the subsequent jump (Padua et al., 2011). Trials 1 and 2 were scored from the front and used to evaluate stance width, foot rotation, initial foot contact, and knee and trunk frontal-plane motion. Trials 3 and 4 were used to assess how participants landed from the jump, knee sagittal-plane motion, trunk sagittal-plane motion, and an overall impression across all of the trials of the jump landing task. Participants were scored off of a 10 item checklist that addressed each of these movements, and a final composite score was calculated by summing all of the items on the LESS-RT (Padua et al., 2011). A copy of the scoring sheet used for recording demographic, anthropometric, and LESS-RT scores is available in Appendix C.

2.4.4 CMJ PF assessment. Prior to the assessment of the CMJ the force plate was calibrated. The assessment of the CMJ PF began with the participant standing on the force platform sampling at 500 Hz, with the participants mass being determined using the weight setting under 'Subject Information' in the software menu. Participants were instructed to keep their hands on their hips while they jumped as high as possible, performing a rapid dip to a self-selected depth which they believed would help them to achieve their greatest jumping height. Jumps that were performed with an arm swing were removed from analysis. Participants performed three jumps, with 30 seconds between jumps as jumping performance has been shown to be maintained with this rest period (Cuk et al., 2016; Pereira et al., 2008). The peak force for

the propulsive phase of the CMJ was determined by visual inspection of the force-time curve (Comfort et al., 2017; Cuk et al., 2014, 2016; Hori et al., 2009) with maximal force being defined as the highest force (excluding body weight) attained prior to take-off of the jump (Comfort et al., 2017). The average of the two best trials (determined by maximal peak force) was used in the calculation of absolute and relative CMJ PF. Absolute CMJ PF was determined by subtracting the subjects mass from the CMJ PF score, and relative CMJ PF was determined by dividing the absolute CMJ PF value by the participants own body mass. The calculation of the DSI was determined using absolute CMJ PF (Comfort et al., 2017). For further details refer to Appendix D. Measures of CMJ PF were assessed in kg's.

2.4.5 IMTP PF assessment. The IMTP was measured using the same force platform as the CMJ testing and was interfaced with the same laptop computer. Participants were asked to adopt a posture at which they would start the second pull phase of the clean (Comfort et al., 2017). Hip flexion angles between 124-175 degrees and knee angles between 120-150 degrees were allowed as per previous research (Brady et al., 2018; Comfort et al., 2017), with participants encouraged to assume a position as close to 130-150 degrees of knee flexion and 145 degrees of hip flexion as possible as these positions have been suggested to maximize force output (Brady et al., 2018). To ensure acceptable position, a handheld goniometer was used to assess hip and knee angles (see Appendix E). An immovable collarless steel bar was positioned around mid-thigh in a customized bracket to place the bar at a point that allowed the participant to assume the IMTP position, with the bar just below the crease of the hip (Comfort et al., 2017). The participants hands were strapped to the bar using standard lifting straps (Comfort et al., 2017). Participants were instructed to maintain a stable position (as verified by visual inspection by the researcher) and then given a countdown of '3,2,1, pull!' (Comfort et al., 2017). Minimal

pretension was allowed to ensure that there was no slack in the participant's body or the IMTP rig prior to the initiation of the pull. Participants performed 3 maximal effort IMTPs (Comfort et al., 2017). Each maximal effort IMTP was performed for 5 seconds (Comfort et al., 2017; Drake, Kennedy, & Wallace, 2017), with participants being given strong verbal encouragement for each trial. 2 minutes of rest was given between each trial (Comfort et al., 2017). The height of the bar and the resultant joint angles were replicated between trials (Comfort et al., 2017). Maximum force (excluding body weight) recorded from the force-time curve during the 5 second IMTP trial was reported as the peak force, and the mean of the best two trials (based on peak force) was used for calculation of absolute and relative IMTP PF. Absolute IMTP PF was determined by subtracting the subjects' body mass from the IMTP PF score, and relative IMTP PF was determined by dividing the absolute IMTP PF score by the participant's own body mass. Absolute IMTP PF was used for calculation of the DSI (Comfort et al., 2017; Haff et al., 2005, 1997). For visual reference of this procedure refer to Appendix F. Measures of IMTP PF were assessed in kg's.

2.4.6 Dynamic Strength Index calculation. The calculation for the DSI was the average of the best two trials of absolute CMJ PF divided by the average of the best two trials of absolute IMTP PF and reported as a numeric value.

2.4.7 F-v profile assessment. Participants performed two single maximum effort CMJs under 5 different loading conditions in ascending order: unloaded, and with the addition of 25%, 50%, 75%, and 100% of body mass (García-Ramos et al., 2015; Mundy et al., 2016, 2017). Body mass for the lower body F-v profile was determined using a digital scale and recorded to the nearest 0.1 kg. Additional loads (25-100% body mass) were applied by positioning a standard Olympic barbell across the posterior aspect of the shoulders, whereas a wooden bar of

negligible mass (0.5kg) was used for the unloaded condition (Mundy et al., 2016, 2017). To perform each CMJ, subjects stood upright before quickly squatting to a self-selected depth of approximately 90 degrees of knee flexion and jumping immediately as high as possible without pausing (Hori et al., 2009; Mundy et al., 2017). Verbal encouragement was given by providing feedback of the velocity reached in each repetition to motivate the participant (Garnacho-Castaño et al., 2015). A 1-minute rest period was provided between each CMJ, with 2 minutes provided between each load (Nibali, Chapman, Robergs, & Drinkwater, 2013b). The placement of the drawstring encoder put the PowerTool5 so that it was vertically under the path of the lift, as specified in the PowerTool5 users' manual (*GymAware User Guide*, n.d.). Peak velocity data was written onto a recording sheet and subsequently entered into a customized Excel spreadsheet for analysis to compute the slope of the lower body F-v profile for each participant. The slope of the lower body F-v profile was determined using the Excel formula '=slope(known_y's, known_x's)', with y values being peak velocity scores and x values being the total load (including bodyweight) for each jump trial (Jovanovic & Flanagan, 2014). For visual reference of this procedure refer to Appendix G.

2.5 Statistical analysis

Statistical analysis was conducted with Statistica software (Tibco Statistica 13.3, TIBCO Software Inc., 3307 Hillview Avenue, Palo Alto, CA, U.S.A.). The purpose of the primary analysis was to identify significant correlations between the DSI and the slope of the lower body F-v profile, as well as correlations with components of the DSI and lower body F-v profile that represented each participant's ballistic and maximal force capabilities. The purpose of the secondary analysis was to determine if there was a difference in performance variables between females and males, as well as to evaluate performance variable differences between stronger and

weaker participants. Despite multiple correlational evaluations the Bonferroni correction was not utilized due to the irrelevancy of Type I error in the present study, in addition to limiting the likelihood of a Type II error (Gelman, Hill, & Yajima, 2012; Perneger, 1998).

2.5.1 Primary analysis. Variables for the primary analysis were the DSI, lower body F-v profile slope, CMJ peak force, IMTP peak force, unloaded CMJ peak velocity, and +100% bodyweight CMJ peak velocity. Normality for each variable was assessed using the Shapiro-Wilk test. As some of the variables were not normally distributed, Spearman's rank-order correlation was used to identify significant correlations. Partial correlations controlling for mass were also calculated between these performance variables, as body size has been shown to confound parameters of physical performance tasks. Statistical significance for this study was set at $p \leq 0.05$ (Bonett & Wright, 2000). Other statistically significant correlations were evaluated as <0.1 = trivial, 0.1 to 0.3 = small, 0.3 to 0.5 = moderate, 0.5 to 0.7 = large, 0.7 to 0.9 = very large, >0.9 = nearly perfect, and 1.0 = perfect (Comfort et al., 2017; Petrakos et al., 2017). In the present study there was no missing data to address.

2.5.2 Secondary analysis. Participants were split into a 'stronger' and 'weaker' group based off of relative IMTP scores, with the top 50% being regarded as 'stronger' and the bottom 50% being regarded as 'weaker' (Thomas, Jones, Rothwell, Chiang, & Comfort, 2015). Participants were also split into 'female' and 'male' groups, regardless of any measured performance parameter. The purpose of separating these cohorts was to determine if there were significant differences in measured performance parameters between females and males, as well as stronger and weaker participants. Levene's test was used to assess homogeneity of variances in the assessed variables. As Levene's test yielded significant results, the non-parametric Welch's ANOVA was used to determine between-group differences in DSI, lower body F-v

profile slope, CMJ peak force, IMTP peak force, BW CMJ PV, and +100% BW CMJ PV. Statistical significance was set at $\rho \leq 0.05$.

RESULTS

3.1 Participant characteristics A total of 86 (n=86) participants were recruited and completed this study with 58 females (n=58) and 28 males (n=28). An additional 20 (n=20) were recruited for the study but were unable to complete it due to scheduling conflicts or failure of successful completion of the LESS-RT screening test.

The participants for this study come from a wide variety of athletic backgrounds with participants identifying with badminton (n=1), baseball (n=1), basketball (n=4), climbing (n=1), dance (n=1), gridiron football (n=17), ice hockey (n=14), rugby (n=1), soccer (n=19), swimming (n=3), track and field (n=8), Ultimate Frisbee (n=2), volleyball, (n=6), weightlifting (n=5), and no sport participation (n=3). Participants also had a wide range of competitive level of sport participation including none (n=2), high school/recreational (n=11), collegiate (n=64), international (n=7), and Olympic/professional (n=2).

3.1.1 All participant descriptive characteristics Descriptive characteristics of all participants are listed below in Table 3.1.1.

Table 3.1.1 Descriptive characteristics (all participants)

Variable	Mean	SD	Minimum	Maximum
Height (m)	1.722	0.097	1.557	1.997
Mass (kg)	74.417	16.495	50.833	143.787
Age (years)	22.681	3.097	18.142	30.595
LESS Real Time score	2.046	1.300	0	4
Years in sport	14.715	5.263	0.000	25.000
Years in RT	5.298	3.297	0.167	16.000
Leg length (m)	1.002	0.077	0.882	1.332
Thigh girth (m)	0.579	0.049	0.478	0.808

Note: RT=resistance training

3.1.2 Female participant descriptive characteristics. Descriptive characteristics of all participants are listed below in Table 3.1.2.

Table 3.1.2 Descriptive characteristics (female participants)

Variable	Mean	SD	Minimum	Maximum
Height (m)	1.675	0.069	1.557	1.852
Mass (kg)	66.321	8.738	50.833	102.538
Age (years)	22.349	3.040	18.142	30.595
LESS Real Time score	2.103	1.280	0	4
Years in sport	14.784	5.242	0.000	25.000
Years in RT	4.408	2.894	0.167	16.000
Leg length (m)	0.987	0.079	0.882	1.332
Thigh girth (m)	0.569	0.037	0.510	0.700

Note: RT=resistance training

3.1.3 Male participant descriptive characteristic. Descriptive characteristics of male participants are listed below in Table 3.1.3

Table 3.1.3 Descriptive characteristics (male participants)

Variable	Mean	SD	Minimum	Maximum
Height (m)	1.818	0.072	1.697	1.997
Mass (kg)	91.187	16.215	65.605	143.787
Age (years)	23.369	3.154	18.707	29.940
LESS Real Time score	1.929	1.359	0	4
Years in sport	14.571	5.398	2.000	25.000
Years in RT	7.143	3.363	3.000	15.000
Leg length (m)	1.033	0.062	0.888	1.169
Thigh girth (m)	0.600	0.064	0.478	0.808

Note: RT=resistance training

3.1.4 Stronger participant descriptive characteristics. Descriptive characteristics of stronger participants are listed below in Table 3.1.4. Of this group, 21 participants were female and 22 were male.

Table 3.1.4 Descriptive characteristics (stronger participants)

Variable	Mean	SD	Minimum	Maximum
Height (m)	1.730	0.094	1.557	1.887
Mass (kg)	77.099	16.000	52.820	112.931
Age (years)	22.808	2.736	18.142	29.871
LESS Real Time score	2.876	0.468	2.317	4.400
Years in sport	14.977	4.662	2.000	25.000
Years in RT	5.678	2.990	0.167	13.000
Leg length (m)	0.998	0.066	0.882	1.118
Thigh girth (m)	0.582	0.044	0.503	0.670

Note: RT=resistance training

Weaker participant descriptive characteristics. Descriptive characteristics of weaker participants are listed below in Table 3.1.5. Of this group 37 participants were female and 6 participants were male.

Table 3.1.5 Descriptive characteristics (weaker participants)

Variable	Mean	SD	Minimum	Maximum
Height (m)	1.713	0.100	1.560	1.997
Mass (kg)	71.734	16.731	50.833	143.787
Age (years)	22.553	3.448	18.266	30.595
LESS Real Time score	1.918	0.258		
Years in sport	14.453	5.846	0.000	25.000
Years in RT	4.919	3.573	0.167	16.000
Leg length (m)	1.005	0.087	0.883	1.332
Thigh girth (m)	0.576	0.055	0.478	0.808

Note: RT=resistance training

3.2 Performance results

3.2.1 All participants DSI test results Performance results for all participants DSI tests are listed in Table 3.2.1 below.

Table 3.2.1 DSI test results (all participants)

Variable	Mean	SD	Minimum	Maximum
Hip IMTP Angle (degrees)	144.488	6.651	124.000	156.000
Knee IMTP Angle (degrees)	135.012	6.059	120.000	150.000
A. IMTP PF (kgf)	186.188	72.599	96.617	393.034
R. IMTP PF (kgf/kg)	2.466	0.624	1.446	4.467
A. CMJ PF (kgf)	104.793	36.070	52.871	230.377
R. CMJ PF (kgf/kg)	1.395	0.291	0.895	2.524
DSI	0.585	0.126	0.317	0.945

Note: IMTP = isometric mid-thigh pull, A. = absolute, R. = relative, PF = peak force, DSI = dynamic strength index

3.2.2 All participants F-v profile test results Performance results for the F-v profile test for all participants regardless of sex or strength are listed in Table 3.2.2 below.

Table 3.2.2 F-v profile test results (all participants)

Variable	Mean	SD	Minimum	Maximum
BW PV (m/)	3.173	0.452	2.165	4.475
+25% BW PV (m/s)	2.650	0.340	1.975	3.550
+50% BW PV (m/s)	2.261	0.299	1.695	3.090
+75% BW PV (m/s)	1.956	0.280	1.250	2.690
+100% BW PV (m/s)	1.703	0.279	0.945	2.490
F-v profile slope	-0.020	0.004	-0.033	-0.012

Note: BW PV = bodyweight peak velocity, F-v = Force-velocity

3.3 Spearman rank correlation results

3.3.1 All participants Spearman rank order correlations were deemed significant at $p \leq 0.05$ with a 90% CI, and are displayed in Table 3.3.1 below. Significant correlations are highlighted in Table 3.3.1 below.

Table 3.3.1 – Spearman rank order correlations (all participants)

	A. IMTP PF	**R. IMTP PF**	**A. CMJ PF**	**R. CMJ PF**	**BW PV**	**+100% BW PV**	**DSI**	**Slope**
A. IMTP PF (kgf)								
R. IMTP PF (kgf/kg)	0.83*							
A. CMJ PF (kgf)	0.75*	0.48*						
R. CMJ PF (kgf/kg)	0.46*	0.56*	0.73*					
BW PV (m/s)	0.60*	0.50*	0.59*	0.45*				
+100% BW PV (m/s)	0.70*	0.66*	0.73*	0.67*	0.74*			
DSI	-0.51*	-0.63*	0.11	0.22*	-0.17	-0.16		
F-v profile slope	0.38*	0.10	0.46*	0.09	-0.24*	0.22*	0.01	

Note: * = significant at p≤0.05, A.IMTP PF = absolute isometric mid-thigh pull peak force, R. IMTP PF = relative isometric mid-thigh pull peak force, A. CMJ PF = absolute countermovement jump peak force, R. CMJ PF = relative countermovement jump peak force, BW PV = bodyweight peak velocity, +100% BW PV = +100% bodyweight peak velocity, DSI = dynamic strength index

3.3.1.1. Partial correlations (all participants) Partial correlations were computed controlling for mass and deemed significant at p≤0.05 with a 90% CI, and are highlights in table 3.3.1.1 below.

Table 3.3.1.1 Partial correlations controlling for mass (all participants)

	A. IMTP PF	**R. IMTP PF**	**A. CMJ PF**	**R. CMJ PF**	**BW PV**	**+100% BW PV**	**DSI**	**Slope**
A. IMTP PF (kgf)								
R. IMTP PF (kgf/kg)	0.98*							
A. CMJ PF (kgf)	0.61*	0.57*						
R. CMJ PF (kgf/kg)	0.56*	0.54*	0.98*					
BW PV (m/s)	0.50*	0.50*	0.47*	0.46*				
+100% BW PV (m/s)	0.62*	0.63*	0.58*	0.61*	0.73*			
DSI	-0.56*	-0.61*	0.23*	0.29*	-0.15	-0.13		
F-v profile slope	-0.04	-0.03	-0.02	0.00	-0.70*	-0.07	0.06	

Note: * = significant at p≤0.05, A.IMTP PF = absolute isometric mid-thigh pull peak force, R. IMTP PF = relative isometric mid-thigh pull peak force, A. CMJ PF = absolute countermovement jump peak force, R. CMJ PF = relative countermovement jump peak force, BW PV = bodyweight peak velocity, +100% BW PV = +100% bodyweight peak velocity, DSI = dynamic strength index

3.3.2 Female participants Spearman rank order correlations were computed for all female participants and deemed significant at p≤0.05 with a 90% CI, and are displayed in Table 3.3.2 below. Significant correlations are highlighted in Table 3.3.2 below.

Table 3.3.2 Spearman rank order correlations (female participants)

	A. IMTP PF	R. IMTP PF	A. CMJ PF	R. CMJ PF	BW PV	+100% BW PV	DSI	Slope
A. IMTP PF (kgf)								
R. IMTP PF (kgf/kg)	0.80*							
A. CMJ PF (kgf)	0.32*	0.06						
R. CMJ PF (kgf/kg)	0.18	0.35*	0.72*					
BW PV (m/s)	0.33*	0.35*	0.31*	0.36*				
+100% BW PV (m/s)	0.38*	0.53*	0.41*	0.59*	0.64*			
DSI	-0.61*	-0.68*	0.49*	0.38*	-0.08	-0.07		
F-v profile slope	0.09	-0.14	0.18	-0.09	-0.69*	-0.13	0.11	

Note: * = significant at p≤0.05, A.IMTP PF = absolute isometric mid-thigh pull peak force, R. IMTP PF = relative isometric mid-thigh pull peak force, A. CMJ PF = absolute countermovement jump peak force, R. CMJ PF = relative countermovement jump peak force, BW PV = bodyweight peak velocity, +100% BW PV = +100% bodyweight peak velocity, DSI = dynamic strength index

3.3.2.1 Partial correlations (female participants) Partial correlations were computed controlling for mass and deemed significant at p≤0.05 with a 90% CI, and are displayed in Table 3.3.2.1. Significant correlations are highlighted in Table 3.3.2.1 below.

Table 3.3.2.1 Partial correlations controlling for mass (female participants)

	A. IMTP PF	**R. IMTP PF**	**A. CMJ PF**	**R. CMJ PF**	**BW PV**	**+100% BW PV**	**DSI**	**Slope**
A. IMTP PF (kgf)								
R. IMTP PF (kgf/kg)	0.99*							
A. CMJ PF (kgf)	0.25	0.24						
R. CMJ PF (kgf/kg)	0.23	0.22	0.99*					
BW PV (m/s)	0.38*	0.36*	0.34*	0.33*				
+100% BW PV (m/s)	0.46*	0.44*	0.57*	0.55*	0.68*			
DSI	-0.67*	-0.68*	0.52*	0.53*	-0.09	0.01		
F-v profile slope	-0.09	-0.09	0.00	-0.01	-0.78*	-0.10	0.09	

Note: * = significant at p≤0.05, A.IMTP PF = absolute isometric mid-thigh pull peak force, R. IMTP PF = relative isometric mid-thigh pull peak force, A. CMJ PF = absolute countermovement jump peak force, R. CMJ PF = relative countermovement jump peak force, BW PV = bodyweight peak velocity, +100% BW PV = +100% bodyweight peak velocity, DSI = dynamic strength index

3.3.3 Male participants Spearman rank order correlations were computed for all male participants and deemed significant at p≤0.05 with a 90% CI, and are displayed in Table 3.3.3 below. Significant correlations are highlighted in Table 3.3.3 below.

Table 3.3.3 Spearman rank order correlations (male participants)

	A. IMTP PF	R. IMTP PF	A. CMJ PF	R. CMJ PF	BW PV	+100% BW PV	DSI	Slope
A. IMTP PF (kgf)								
R. IMTP PF (kgf/kg)	0.81*							
A. CMJ PF (kgf)	0.64*	0.32						
R. CMJ PF (kgf/kg)	0.37	0.58*	0.53*					
BW PV (m/s)	0.43*	0.31	0.39*	0.22				
+100% BW PV (m/s)	0.30	0.45*	0.18	0.43*	0.64*			
DSI	-0.51*	-0.56*	0.15	0.16	-0.13	-0.16		
F-v profile slope	0.04	-0.18	0.19	-0.23	-0.58*	-0.24	0.03	

Note: * = significant at p≤0.05, A.IMTP PF = absolute isometric mid-thigh pull peak force, R. IMTP PF = relative isometric mid-thigh pull peak force, A. CMJ PF = absolute countermovement jump peak force, R. CMJ PF = relative countermovement jump peak force, BW PV = bodyweight peak velocity, +100% BW PV = +100% bodyweight peak velocity, DSI = dynamic strength index

3.3.3.1 Partial correlations (male participants) Partial correlations were computed controlling for mass and deemed significant at p≤0.05 with a 90% CI, and are displayed in Table 3.3.3.1. Significant correlations are highlighted in Table 3.3.3.1 below.

Table 3.3.3.1 Partial correlations controlling for mass (male participants)

	A. IMTP PF	**R. IMTP PF**	**A. CMJ PF**	**R. CMJ PF**	**BW PV**	**+100% BW PV**	**DSI**	**Slope**
A. IMTP PF (kgf)								
R. IMTP PF (kgf/kg)	0.99*							
A. CMJ PF (kgf)	0.54*	0.51*						
R. CMJ PF (kgf/kg)	0.50*	0.49*	0.99*					
BW PV (m/s)	0.40*	0.39*	0.39*	0.37				
+100% BW PV (m/s)	0.39*	0.43*	0.31	0.34	0.69*			
DSI	-0.61*	-0.63*	0.31	0.34	-0.09	-0.12		
F-v profile slope	-0.13	-0.10	-0.16	-0.11	-0.84*	-0.25	0.01	

Note: * = significant at $p \leq 0.05$, A.IMTP PF = absolute isometric mid-thigh pull peak force, R. IMTP PF = relative isometric mid-thigh pull peak force, A. CMJ PF = absolute countermovement jump peak force, R. CMJ PF = relative countermovement jump peak force, BW PV = bodyweight peak velocity, +100% BW PV = +100% bodyweight peak velocity, DSI = dynamic strength index

3.3.4 Stronger participants Spearman rank order correlations were computed for all stronger participants and deemed significant at $p \leq 0.05$ with a 90% CI, and are displayed in Table 3.3.4 below. Significant correlations are highlighted in Table 3.3.4 below.

Table 3.3.4 Spearman rank order correlations (stronger participants)

	A. IMTP PF	R. IMTP PF	A. CMJ PF	R. CMJ PF	BW PV	+100% BW PV	DSI	Slope
A. IMTP PF (kgf)								
R. IMTP PF (kgf/kg)	0.77*							
A. CMJ PF (kgf)	0.85*	0.56*						
R. CMJ PF (kgf/kg)	0.41*	0.49*	0.72*					
BW PV (m/s)	0.56*	0.34*	0.59*	0.35*				
+100% BW PV (m/s)	0.58*	0.47*	0.69*	0.51*	0.71*			
DSI	-0.19	-0.29	0.29	0.61*	0.07	0.15		
F-v profile slope	0.50*	0.29	0.49*	0.14	-0.17	0.31*	-0.05	

Note: * = significant at p≤0.05, A.IMTP PF = absolute isometric mid-thigh pull peak force, R. IMTP PF = relative isometric mid-thigh pull peak force, A. CMJ PF = absolute countermovement jump peak force, R. CMJ PF = relative countermovement jump peak force, BW PV = bodyweight peak velocity, +100% BW PV = +100% bodyweight peak velocity, DSI = dynamic strength index

3.3.4.1 Partial correlations (stronger participants) Partial correlations were computed controlling for mass and deemed significant at p≤0.05 with a 90% CI, and are displayed in Table 3.3.4.1. Significant correlations are highlighted in Table 3.3.4.1 below.

Table 3.3.4.1 Partial correlations controlling for mass (stronger participants)

	A. IMTP PF	R. IMTP PF	A. CMJ PF	R. CMJ PF	BW PV	+100% BW PV	DSI	Slope
A. IMTP PF (kgf)								
R. IMTP PF (kgf/kg)	0.99*							
A. CMJ PF (kgf)	0.47*	0.42*						
R. CMJ PF (kgf/kg)	0.43*	0.40*	0.98*					
BW PV (m/s)	0.29	0.26	0.35*	0.34*				
+100% BW PV (m/s)	0.41*	0.41*	0.39*	0.45*	0.63*			
DSI	-0.27	-0.31*	0.68*	0.73*	0.17	0.21		
F-v profile slope	0.01	0.06	-0.05	0.00	-0.77*	-0.05	-0.04	

Note: * = significant at p≤0.05, A.IMTP PF = absolute isometric mid-thigh pull peak force, R. IMTP PF = relative isometric mid-thigh pull peak force, A. CMJ PF = absolute countermovement jump peak force, R. CMJ PF = relative countermovement jump peak force, BW PV = bodyweight peak velocity, +100% BW PV = +100% bodyweight peak velocity, DSI = dynamic strength index

3.3.5 Weaker participants Spearman rank order correlations were computed for all weaker participants and deemed significant at p≤0.05 with a 90% CI, and are displayed in Table 3.3.5 below. Significant correlations are highlighted in Table 3.3.5 below.

Table 3.3.5 Spearman rank order correlations (weaker participants)

	A. IMTP PF	**R. IMTP PF**	**A. CMJ PF**	**R. CMJ PF**	**BW PV**	**+100% BW PV**	**DSI**	**Slope**
A. IMTP PF (kgf)								
R. IMTP PF (kgf/kg)	0.56*							
A. CMJ PF (kgf)	0.58*	0.12						
R. CMJ PF (kgf/kg)	0.14	0.36*	0.66*					
BW PV (m/s)	0.49*	0.42*	0.39*	0.31*				
+100% BW PV (m/s)	0.46*	0.50*	0.56*	0.59*	0.68*			
DSI	-0.28	-0.41*	0.57*	0.66*	0.00	0.17		
F-v profile slope	0.26	-0.20	0.41*	0.01	-0.43*	0.08	0.15	

Note: * = significant at p≤0.05, A.IMTP PF = absolute isometric mid-thigh pull peak force, R. IMTP PF = relative isometric mid-thigh pull peak force, A. CMJ PF = absolute countermovement jump peak force, R. CMJ PF = relative countermovement jump peak force, BW PV = bodyweight peak velocity, +100% BW PV = +100% bodyweight peak velocity, DSI = dynamic strength index

3.3.5.1 Partial correlations (weaker participants) Partial correlations were computed controlling for mass and deemed significant at p≤0.05 with a 90% CI, and are displayed in Table 3.3.5.1. Significant correlations are highlighted in Table 3.3.5.1 below.

Table 3.3.5.1 Partial correlations controlling for mass (weaker participants)

	A. IMTP PF	R. IMTP PF	A. CMJ PF	R. CMJ PF	BW PV	+100% BW PV	DSI	Slope
A. IMTP PF (kgf)								
R. IMTP PF (kgf/kg)	0.98*							
A. CMJ PF (kgf)	0.37*	0.36*						
R. CMJ PF (kgf/kg)	0.32*	0.32*	0.99*					
BW PV (m/s)	0.44*	0.43*	0.39*	0.36*				
+100% BW PV (m/s)	0.51*	0.49*	0.66*	0.61*	0.69*			
DSI	-0.45*	-0.47*	0.64*	0.68*	0.01	0.20		
F-v profile slope	-0.14	-0.16	0.03	0.01	-0.75*	-0.08	0.13	

Note: * = significant at p≤0.05, A.IMTP PF = absolute isometric mid-thigh pull peak force, R. IMTP PF = relative isometric mid-thigh pull peak force, A. CMJ PF = absolute countermovement jump peak force, R. CMJ PF = relative countermovement jump peak force, BW PV = bodyweight peak velocity, +100% BW PV = +100% bodyweight peak velocity, DSI = dynamic strength index

3.4 Welch's F-test results

3.4.1 Sex groups (all participants) Welch's F test was used to compare male and female participant performance characteristics regardless of strength levels. Results were deemed significant at $p<0.05$, with a 90% CI and are displayed in Table 3.4.1 below. Significant differences were found between males and females in A. IMTP PF ($F(1, 47.08)=65.35$, $p<0.001$), R. IMTP PF ($F(1,54.63)=25.44$, $p<0.001$), A. CMJ PF ($F(1,33.64)=57.46$, $p<0.001$), R. CMJ PF ($F(1,39.70)=19.46$, $p<0.001$), BW PV ($F(1,46.80)=25.75$, $p<0.001$), +100% BW PV ($F(1,59.00)=42.52$, $p<0.001$), and F-v profile slope ($F(1,59.04)=15.70$, $p<0.001$).

Table 3.4.1 Welch's F-test sex groups (all participants)

	Female mean (±SD)	Male mean (±SD)	Welch F	Welch p
A. IMTP PF (kgf)	146.04 (±28.725)	269.35 (±64.929)	65.35*	0.00
R. IMTP PF (kgf/kg)	2.21 (±0.433)	2.97 (±0.656)	25.44*	0.00
A. CMJ PF (kgf)	85.63b(±15.116)	144.48 (±34.514)	57.46*	0.00
R. CMJ PF (kgf/kg)	1.29 (±0.215)	1.59 (±0.325)	19.46*	0.00
BW PV (m/s)	2.997 (±0.351)	3.540 (±0.418)	25.75*	0.00
+100% BW PV(m/s)	1.575 (±0.210)	1.969 (±0.207)	42.52*	0.00
DSI	0.60 (±0.132)	0.55 (±0.106)	2.18	0.14
F-v profile slope	-0.021 (±0.003)	-0.017 (±0.003)	15.70*	0.00

Note: * = significant at p≤0.05, A.IMTP PF = absolute isometric mid-thigh pull peak force, R. IMTP PF = relative isometric mid-thigh pull peak force, A. CMJ PF = absolute countermovement jump peak force, R. CMJ PF = relative countermovement jump peak force, BW PV = bodyweight peak velocity, +100% BW PV = +100% bodyweight peak velocity, DSI = dynamic strength index

3.4.2 Strength groups (all participants) Welch's F test was used to compare stronger and weaker participant performance characteristics regardless of sex. Results were deemed significant at p≤0.05, with a 90% CI and are displayed in Table 3.5.1 below. Significant differences were found between stronger and weaker participants in A. IMTP ($F(1,61.93)=54.08$, $p<0.001$), R. IMTP PF ($F(1,64.21)=146.23$,$p<0.001$), A. CMJ PF ($F(1,68.48)=13.58$, $p<0.001$), R. CMJ PF ($F(1,74.39)=16.36$, $p<0.001$), BW PV ($F(1,82.76)=17$, $p<0.001$), +100% BW PV ($F(1,78.10)=30.10$, $p<0.001$), and DSI ($F(1,78.10)=38.63$, $p<0.001$).

Table 3.4.2 Welch's F-test strength groups (all participants)

	Stronger participants mean (±SD)	Weaker participants mean (±SD)	Welch F	Welch p
A. IMTP PF (kgf)	231.35 (±71.984)	141.01 (±36.159)	54.08*	0.00
R. IMTP PF (kgf/kg)	2.96 (±0.473)	1.97 (±0.253)	146.23*	0.00
A. CMJ PF (kgf)	118.17 (±40.901)	91.41 (±24.367)	13.58*	0.00
R. CMJ PF (kgf/kg)	1.51 (±0.312)	1.27 (±0.214)	16.36*	0.00
BW PV (m/s)	3.35 (±0.439)	2.98 (±0.388)	17.00*	0.00
+100% BW PV(m/s)	1.84 (±0.240)	1.56 (±0.242)	30.10*	0.00
DSI	0.51 (±0.089)	0.65 (±0.119)	38.63*	0.00
F-v profile slope	-0.020 (±0.004)	-0.020 (±0.004)	0.40	0.53

Note: * = significant at $p<0.05$, A.IMTP PF = absolute isometric mid-thigh pull peak force, R. IMTP PF = relative isometric mid-thigh pull peak force, A. CMJ PF = absolute countermovement jump peak force, R. CMJ PF = relative countermovement jump peak force, BW PV = bodyweight peak velocity, +100% BW PV = +100% bodyweight peak velocity, DSI = dynamic strength index

DISCUSSION

The primary results of the present study show that the DSI is not correlated to the slope of the lower-body F-v profile. There were no significant correlations between the DSI and the F-v profile slope across all participants, or when the present cohort was divided by sex characteristics or strength characteristics. This finding suggests that the primary hypothesis, that a correlation exists between the DSI value and the F-v profile slope, is not supported.

The secondary results of the present study suggest that measures of ballistic and isometric peak force are correlated to measures of CMJ PV across a series of loading conditions. There were significant correlations between measures of ballistic and isometric peak force and CMJ PV across loading conditions across all participants, and when the present cohort was divided by sex characteristics or strength characteristics. This suggests that both ballistic peak force and isometric peak force are significantly correlated with measures of peak propulsive velocity during the unloaded and loaded CMJ.

4.1 There were no significant correlations between DSI and lower-body F-v profile slope. It is possible that inherent differences in the testing protocols may have resulted in a lack of significant correlations between the results of the DSI and F-v profile tests. Thomas, Jones, & Comfort (2015) have suggested that the biomechanical differences between the IMTP and the CMJ, including the types of muscular contraction involved (i.e. IMTP consisting of an isometric muscle action, whereas the CMJ consists of eccentric, isometric, and concentric muscle actions) may mean that some measures of IMTP performance may be unrelated to CMJ performance across a series of different loading conditions. It has been suggested that testing protocols are most effective when considering the biomechanical characteristics of the involved protocols (Brady et al., 2018; Thomas, Jones, & Comfort, 2015), and it may be that the biomechanical

differences between involved testing protocols contributed to a lack of relationship between results Indeed, Morales-Artacho et al. (2018) make note of the importance of task-specificity when it comes to assessing measures of explosive muscular performance.

One potential difference between testing protocols may have been the differences in joint angles necessary to perform the IMTP versus the CMJ. Because of the L-t and F-v relationships of skeletal muscle, maximal voluntary torque around a joint is dependent on the angle and angular velocity around a joint (Tillin, Pain, & Folland, 2018). The differences in joint angle adopted between the IMTP and the CMJ in this study may have impacted agonist muscle groups, and therefore influenced the lack of statistical significant relationships between testing protocols that involve the IMTP and the CMJ. While isometric strength has been associated with measures of dynamic strength, the best transfer between these measures occurs at specific joint angles with less transfer to alternate joint angles (and therefore different muscle lengths) (Baiget, Corbi, Fuentes, & Fernández-Fernández, 2016). Additionally, it is possible that the increases in load associated with the F-v profile protocol may have altered the jumping mechanics of the participants, and therefore kinematic and kinetic movement patterns associated with the loaded CMJ (Feeney et al., 2016) when compared to the unloaded CMJ condition that was used in the protocol for DSI evaluation. The patterns that are associated with the CMJ that can be changed with additional loading may affect the development of maximal force, RFD, the activation and synchronization of motor units, and dynamic joint stability (Martínez-Cava, Morán-Navarro, Sánchez-Medina, González-Badillo, & Pallarés, 2018), with a change in these variables likely affecting performance parameters.

It is possible that there are inherent differences between isometric and dynamic activity that may have resulted in no significant correlations between the results of the testing protocols.

Nuzzo, McBride, Cormie, & McCaulley (2008) suggest that the validity of isometric tests to correlate with performance in dynamic activity could be questioned as isometric tests are not specific to the dynamic movement patterns associated with human performance. Additionally, performance in jumping tasks is determined by force generated as well as movement velocity and it is likely that these variables have a more complex relationship during dynamic tasks than with isometric tasks, where no velocity variable exists and instead maximal force is the key performance attribute (Thomas, Jones, Rothwell, et al., 2015).

It is possible that the F-v profile protocol was not performed across a broad enough range of loading conditions to encompass the full spectrum of F-v demands (i.e. velocity favoured demands compared to force favoured demands). A previous investigation by Feeney et al. (2016) has suggested that one issue with F-v profile evaluation is that obtained force and velocity data may cover a relatively small portion of their entire intervals. In other words, the selected loading conditions for the evaluation of the F-v profile may not necessarily encompass a wide enough range to represent the low-load velocity-favoured characteristics as well as the high-load force-favoured characteristics. This finding suggests that in order to truly represent the F-v capabilities of an individual the spread of loading conditions must be relatively light enough when compared to the 1RM of the exercise to represent velocity-favoured characteristics and relatively heavy enough to represent force-favoured characteristics. This range of loading conditions may be difficult to obtain with a ballistic lower body exercise. Morales-Artacho et al. (2018) found that evaluation of the F-v profile from the CMJ exercise are inherently closer to force-characteristics than velocity characteristics. This may be due to the fact that the unloaded CMJ represents the minimal loading condition of the participants' bodyweight, meaning that the lightest possible loading condition for the loaded CMJ test would be the relative percentage of

1RM CMJ that the participants' bodyweight represents. Turner, Unholz, Potts, & Coleman (2012) indicate that it is possible to perform a 1RM jump squat, which demonstrates that the unloaded CMJ would be a relative percentage of the load necessary to perform a 1RM CMJ. Jovanovic & Flanagan (2014) suggest that the F-v profile should be assessed across loading conditions of at least 30-85% of the 1RM for the exercise to represent the entire F-v interval of the individual. In the present study the 1RM CMJ was not evaluated, and as such the full spectrum of force and velocity demands may not have been represented by the selected loading conditions. The inability of the F-v profile to accurately evaluate the entire spectrum of force and velocity demands may have contributed to the lack of significant correlation with the DSI found in this study.

There are suggestions in the literature that the F-v profile slope may be more dependent on actual strength performance than the DSI. Comfort et al. (2018) demonstrate that the DSI ratio should not be considered alone, and the maximal isometric strength of the individual should be considered prior to relying on the DSI ratio for guiding training programming. The DSI ratio itself cannot be used to determine an individual's strength levels (Thomas, Jones, & Comfort, 2015), but instead reflects how the individual expressed force in the testing protocol that they participated in (J. J. McMahon et al., 2017). As such, the DSI should not be used as a means of comparing different individuals. The F-v profile, however, has been recommended by some authors as a means of comparing performance in resistance training exercise between individuals (Jovanovic & Flanagan, 2014). The F-v profile, therefore, may represent an absolute or relative measurement of muscular performance that is influenced by the strength levels of the individual as opposed to an internal comparison of performance capability.

The DSI was not correlated to measures of loaded or unloaded CMJ PV in the present study. This may be explained by the suggestions in the literature that the DSI is not a measure of external muscular performance, whereas the peak velocity attained in the CMJ is a measure of external muscular performance. The CMJ PV value is a directly measured value of performance which may be correlated to maximal strength performance, and as such it is likely that individuals with different CMJ PV performance can have similar DSI values (Thomas, Jones, & Comfort, 2015). Previous research by J. J. McMahon et al. (2017) found that people with a lower DSI produced higher propulsive CMJ PV, however it is likely that this was related to greater measures of isometric strength in their subjects. In the present study there were correlations between IMTP PF and BW PV, which appears to be in line with these findings. While the DSI is a reflection of strength expression it cannot be used to evaluate strength performance in individuals and it is possible that the DSI is similarly limited in regards to evaluating measures of jumping performance, and in particular CMJ PV. This finding confirms the suggestion that practitioners should concern themselves with measures of maximal strength and power performance over the DSI value.

Interestingly, the DSI was positively correlated with measures of +100% BW CMJ PV in the stronger female cohort, but not in any other cohort. There were significant correlations between CMJ PF and DSI in this cohort, as well as significant correlations between CMJ PF and +100% BW CMJ PV. It is possible that the significant correlation between +100% BW CMJ PV and DSI in this cohort is related to the finding that higher measures of +100% BW CMJ PV were associated with higher amounts of CMJ PF in this cohort, and therefore would be associated with higher DSI values.

4.2 The F-v profile slope is not correlated with measures of maximal ballistic or isometric peak force. When controlling for mass, there were no significant correlations between F-v profile slope and IMTP PF across all participants, however without controlling for mass there were significant correlations with the F-v profile slope and IMTP PF. This may be because of the confounding nature body size has on measures of muscular performance. While relative isometric force production values have been suggested to be more important to jumping task performance than absolute isometric force production values (Thomas, Jones, Rothwell, et al., 2015) this finding is in line with previous suggestions that absolute values of strength and power increase with body size (Markovic et al., 2014; Nikolaidis et al., 2018). These higher values of absolute strength and power may have confounded the relationship between IMTP PF and the F-v profile slope. Relative IMTP PF was not correlated with the F-v profile slope in the entire cohort. Khamoui et al. (2011) report that relative IMTP PF is correlated with vertical jump peak velocity, which was also the case in the present study and is a component of the evaluation of the F-v profile. However, this finding suggests that the IMTP PF does not correlate with changes in CMJ PF performance across a range of loading conditions in ballistic lower body exercises. It is possible that this is due to the change in jumping performance output that is associated with increases in jumping load. Pierre Samozino et al. (2012) suggest that the optimal load for maximizing power (and therefore propulsive velocity) in lower-body ballistic movements is the individual's own bodyweight. This may be related to changes in countermovement magnitude associated with changes in load that affect movement patterns, development of maximal force, RFD, activation and synchronization of motor units, and dynamic joint stability (Martínez-Cava et al., 2018). Different loading conditions may have affected the changes in movement patterns in different ways (Feeney et al., 2016), and as such

the IMTP PF was not related to the measure of change in performance of the CMJ PV across different loading conditions.

The absolute values of CMJ PF were correlated with F-v profile slope across all participants without controlling for mass. When controlling for mass, there were no significant correlations. Again, this may be due to the confounding nature that body size has on measures of muscular performance and the importance of considering this when evaluating measures of athletic performance should not be understated. Relative CMJ PF was not correlated with the F-v profile slope in any of the participants. The ability to generate CMJ PF in an unloaded condition is not reflective of the change in velocity attained in the CMJ across loading conditions. This is supported by Jovanovic & Flanagan (2014), who suggest that different individuals possess different F-v characteristics which would impact their ability to generate high velocities across different loading conditions. This finding suggests that the ability to produce CMJ PF, while correlated with peak velocity performance in single instances of unloaded and loaded CMJs in the present study, is not related to change in performance parameters associated with changing loading conditions. Feeney et al. (2016) suggest that the F-v relationship may considerably depend on joint angles adopted during CMJs and that higher loads in the CMJ may change jumping mechanics, therefore altering kinematic and kinetic movement patterns and confounding the F-v relationship.

4.3 The DSI is correlated with measures of isometric and ballistic strength.

Measures of IMTP PF were significantly negatively correlated to DSI values across the entire cohort. This is supported by previous findings in the literature that suggest that individuals with low DSI scores tend to be notably stronger based on IMTP PF than those with high DSI scores (Comfort et al., 2018), and that greater isometric peak force values tend to negatively affect the

DSI value (Bishop, Read, Lake, Loturco, & Turner, 2018). This is because IMTP PF forms the denominator in the calculation of the DSI, with larger denominators being associated with lower ratios when calculated.

Measures of absolute and relative CMJ PF were positively correlated to DSI values across all participants when controlling for mass. Without controlling for mass, there was no correlation with absolute CMJ PF and DSI values. As the CMJ PF is the numerator of the calculation of the DSI ratio, it stands to reason that higher CMJ PF value would be related to higher DSI values. However, it is interesting that the correlations between CMJ PF and the DSI were relatively weak compared to those between the IMTP PF and the DSI ratio. This may be because of the differences in the time available to perform the CMJ and the IMTP, with the CMJ being limited by time whereas the IMTP was not in the present study. Muscle stimulation does not reach a maximum level instantaneously but instead takes time to develop maximal stimulation due to the dynamics of motor neuron pool excitation and central nervous system commands (Van Hooren & Zolotarjova, 2017). Tillin et al. (2018) found that ballistic force represents a proportion of maximal voluntary force production, as the time available for force production in these movements is an intrinsic limiting factor for maximal force production. The neuromuscular factors which would be favourable for high amounts of ballistic force production would also be favourable for high amounts of isometric force production, however the ability of the individual to access their maximal force capability during a ballistic contraction would be limited by the time required to perform that exercise. As the IMTP PF in this study is not limited by time, participants were capable of fully expressing their maximal force capabilities regardless of factors which are advantageous for faster force development (i.e. higher proportion of type II muscle fibres, higher RFD). As a result, the denominator in the DSI calculation was more likely

to have a higher value, and therefore greater influence on the DSI than the numerator of the calculation. As the values of IMTP PF were larger than the values of CMJ PF it is appears that they had a stronger relationship with the DSI value.

The DSI is significantly negatively correlated with measures of IMTP PF in males, but there are no significant correlations with measures of CMJ PF in this cohort. It is possible that the males in this study had achieved a level of maximal strength whereby, due to the limitations on force production in ballistic movements, the influence of CMJ PF on the DSI may be less than the IMTP PF. Secomb et al. (2016) suggest that it is possible that there is a 'ceiling effect' of the influence of maximal strength on dynamic strength or jumping performance. It is possible that this 'ceiling effect' of the influence of maximal strength on dynamic force production is influenced by the intrinsic limitations of force production, such as time available to produce force. According to Van Hooren & Zolotarjova (2017) muscle stimulation does not reach a maximum level instantaneously and takes time to reach maximal force development. As the CMJ is a movement that takes ~250ms (Beattie, Carson, Lyons, & Kenny, 2017), the time to develop force in the CMJ is limited and as such very high amounts of maximal force would be inaccessible.

The DSI is significantly negatively correlated with IMTP PF and significantly positively correlated with CMJ PF in the female cohort. It is interesting that CMJ PF had significant positive correlations with the DSI value in the female cohort in the present study. It is possible that the females in this study had not yet achieved a high enough level of maximal strength to experience the potential 'ceiling effect' suggested by Secomb et al. (2016). The lower values of IMTP PF, as well as the potential absence of the 'ceiling effect' on dynamic muscular

performance in relation to maximal isometric strength, may have resulted in the CMJ PF being more associated with the DSI value in the female cohort than the male cohort.

There were no significant correlations between the DSI and absolute IMTP PF in the stronger cohort, but there were significant correlations between DSI and relative IMTP PF as well as absolute and relative CMJ PF in the stronger cohort. It appears to be that when subjects are stratified by IMTP PF, the positive correlation between CMJ PF and the DSI value becomes stronger. J. J. McMahon et al. (2017) suggest that jumping strategy may affect DSI values and that, in addition to being a reflection of the accessible strength of an individual compared to their maximal strength, the DSI value is also reflective of the jumping strategy that the testing employed. It is possible that despite identical instruction the jumping strategy adopted by this cohort may have influenced their ability to generate CMJ PF. Additionally, neuromuscular factors such as greater leg stiffness, higher RFD, intermuscular synchronization, and greater Type II fiber distribution which favor rapid amounts of force generation (Cormie et al., 2011a; Suchomel et al., 2016) that are intrinsic to the individual may have resulted in some members of this cohort generating a higher CMJ PF, therefore resulting in a higher DSI value.

There were significant negative correlations between DSI and IMTP PF and significant positive correlations between DSI and CMJ PF in the weaker group. As supported in the literature, higher values of IMTP PF tended to be associated with lower DSI values (J. J. McMahon et al., 2017). In regards to the significant positive correlation between DSI and CMJ PF in this cohort, it is possible that the CMJ PF would have a significant influence on the DSI because of the smaller denominator in the calculation of the DSI ratio.

4.4 The F-v profile slope is correlated with measures of CMJ PV. This study found that the F-v profile slope was negatively correlated with measures of BW CMJ PV. This finding

was corroborated by González-Badillo, Jiménez-Reyes, & Ramírez-Lechuga (2017), who report that lower F-v slope values are attained by subjects who have higher contraction velocities in the investigated exercises. Tuner et al. (2012) reported that peak jump velocities attained during the lightest load of jump squats performed across a series of loading conditions had the greatest influence on changes of power output between conditions, and it is possible that this result is supported by the present study. Jovanovic & Flanagan (2014) suggest that a lower slope value is associated with less relative change in exercise velocity across loading conditions, which may be associated with neuromuscular conditions that favour high levels of force production. This may be supported by the finding in the present study that measures of unloaded CMJ PV were correlated with measures of +100% BW CMJ PV, suggesting that the neuromuscular conditions which favour high PV in the unloaded CMJ also contribute to higher peak velocity in the heavy load +100% BW CMJ condition. These findings would suggest that the participants in the present study who generated high amounts of CMJ PF were also capable of generating relatively high amounts of CMJ PV across different loading conditions, therefore resulting in less spread across loading conditions of measured PV values.

There were no correlations between +100% BW CMJ PV and the F-v profile slope when controlling for mass. Without controlling for mass there were weak significant correlations between +100% BW CMJ PV and the F-v profile slope across all participants. The finding that there were significant correlations between +100% BW CMJ PV and the F-v profile slope without controlling for mass suggest that the body size of participants may confound the relationship of these two variables, with the confounding affect body size has on jumping performance having previously been reported. As suggested by Turner et al. (2012) it appears

that the peak velocities attained in the lightest CMJ condition had the greatest influence on changes in CMJ PV.

It is interesting that BW CMJ PV was correlated with +100% BW CMJ PV across the entire cohort and in every subgroup analyzed. This may be explained by the suggestion of relative intensity-velocity 'bands' described by Jovanovic & Flanagan (2014). According to the F-v relationship, the lighter the load relative to maximal strength the higher the velocity of movement that can be achieved. Exercises that are performed at the same relative intensity can be lifted at a similar velocity, regardless of changes in absolute value of the exercise load (Jovanovic & Flanagan, 2014). In the case of the present study the lightest load used in the F-v profile evaluation was the participant's bodyweight, which was also the loading condition that allowed for the highest CMJ PV values. All loading conditions used were relative intensities of an untested 1RM CMJ and a higher BW CMJ PV could be correlated with a higher +100% BW CMJ PV because this loading condition was representative of a lower relative intensity and therefore could be lifted at a higher velocity as it was further from the maximal CMJ (1RM CMJ) load.

The significant correlations between BW CMJ PV and +100% BW CMJ PV appear to be slightly stronger in weaker participants when compared to the entire cohort. In the present study measures of +100% BW CMJ PV were significantly associated with measures of maximal isometric and ballistic strength, and higher amounts of maximal strength have been associated with higher concentric velocity in resistance training exercises (Jovanovic & Flanagan, 2014). This would explain the relationship between higher levels of maximal strength and higher CMJ PV in the present study; for stronger individuals the loading conditions would represent a relatively lighter load compared to their 1RM in the CMJ exercise. According to the F-v

relationship, these relatively lighter loads could be lifted at higher velocities. The stronger correlation between the BW CMJ PV and +100% BW CMJ PV in the weaker cohort is an interesting finding. This may be explained by the fact that the stronger cohort may have achieved a 'ceiling' affect in the influence of muscular strength on jumping performance, as suggested by Suchomel et al. (2016) and therefore higher BW CMJ PV would be affected by factors of jump performance other than muscular strength (i.e. intersegmental co-ordination, jumping strategy, RFD) in the stronger cohort. In the weaker cohort BW CMJ PV may have been influenced more strongly by measures of maximal strength as this group may not yet be experiencing the 'ceiling' effect on power/jump performance associated with high levels of maximal force development. The lower amount of maximal strength capability in the weaker cohort would also mean that the +100% BW CMJ condition was relatively heavier when compared to the 1RM CMJ and as such would not be able to be moved at as high a velocity as the stronger cohort.

4.5 Measures of isometric peak force are correlated with measures of ballistic peak force. There are correlations between IMTP PF and CMJ PF across the entire cohort. This finding is supported by research that has suggested that measures of isometric strength are correlated with dynamic performance measures. Thomas, Jones, Rothwell, et al. (2015), for example, report that IMTP PF is correlated with measures of CMJ PF. It is likely that neuromuscular conditions that are advantageous for high amounts of isometric force generation are also advantageous for dynamic force generation, including higher muscle CSA, greater RFD, increased muscular synchronization, greater tendinous stiffness, more motor unit recruitment, and increased firing frequency (Cormie et al., 2011a; Suchomel et al., 2016).

It should be noted that absolute and relative strength values are almost perfectly correlated when controlling for mass. This significant correlation is logical, as these values are mathematical equivalents of one another: the higher the absolute value of force produced by an individual, the higher the relative value of force that would be produced by the same individual.

Interestingly there were significant correlations between IMTP PF and CMJ PF in males but not in females. This was the case with both absolute and relative IMTP PF and CMJ PF values. It is possible that the lack of significant correlations between IMTP PF and CMJ PF in females is due to intrinsic differences between the sexes such as those described by Márquez et al. (2017) which include different kinetic properties, less neuromuscular control, less muscle thickness, different relative fascicle length, lower RFD, and less lower body displacement in females compared to males. These differences may have influenced the ability of the female participants to access their maximal force potential in ballistic movements, and therefore resulted in a lack of significant correlation between IMTP PF and CMJ PF in this cohort. Additionally, the lack of relationship between measures of maximal strength and jump performance has been reported in the literature, with Beattie et al. (2017) finding no difference in measures of CMJ height performance between stronger and weaker athletes in their evaluated cohort.

It is interesting that the significant correlations between IMTP PF and CMJ PF are weaker in the weak cohort than across all participants. It is possible that neuromuscular characteristics of weaker participants, and in particular the potential for lower amounts of leg and MTU stiffness associated with weaker individuals (Rice et al., 2017), may have limited the ability of weaker individuals to translate their maximal strength potential into CMJ PF.

4.6 Measures of isometric peak force are correlated with measures of CMJ PV.

Measures of IMTP PF were correlated with measures of BW PV across all participants. This

finding supports the results by Townsend et al. (2017) that a higher capacity for muscular contractile strength is associated with better jumping performance and higher jumping velocities. Indeed, the literature abounds with evidence that stronger individuals possess favourable neuromuscular characteristics which form the basis for superior power (and therefore velocity) production (Cormie et al., 2011b).

Measures of absolute and relative IMTP PF were correlated with measures of +100% BW CMJ PV across the entire cohort. The +100% BW CMJ loading condition could be considered a heavy-load ballistic exercise, with performance in such loading conditions being related to maximal muscular strength as the neuromuscular conditions which favour high amounts of force generation contribute to higher amounts of power and velocity generation in loaded ballistic exercises (Cormie et al., 2011b). Higher amounts of maximal force have also been associated with the ability to generate higher amounts of power and velocity across the entire F-v spectrum of an evaluated exercise (Cormie et al., 2011b). It is likely that the neuromuscular conditions in participants which facilitated greater isometric strength generation also contributed to higher peak velocity in the +100% BW CMJ condition. Interestingly, measures of IMTP PF had stronger correlations with +100% BW PV than BW PV. This finding may suggest that measures of maximal isometric strength have a greater influence on loaded ballistic exercises than unloaded ballistic exercises, which further supports the suggestion that high levels of maximal strength are important for athletic performance.

There are correlations between IMTP PF and BW CMJ PV in males and females. This finding is not surprising, as there are reports in the literature that measures of absolute and relative isometric peak force are correlated with measures of jump performance parameters, including peak CMJ propulsive velocity (González-Badillo et al., 2017).

IMTP PF is correlated with +100% BW CMJ PV in males and females. This finding suggests that measures of isometric peak force are correlated with measures of high-load ballistic performance in both males and females regardless of intrinsic sex differences which result in differences in neuromuscular performance.

4.7 Measures of ballistic peak force were correlated with measures of CMJ PV.

Measures of CMJ PF were correlated with BW CMJ PV across the entire cohort both with and without controlling for mass. This finding is to expected, as maximal lower-body strength levels are reflected in many vertical jump performance variables (Sole, n.d.), including jump propulsive PV.

Measures of CMJ PF were correlated with +100% BW CMJ PV across all participants with and without controlling for mass. Cormie et al. (2011b) report that individuals who can produce higher amounts of force are capable of generating greater power and velocity across the spectrum of F-v demands used in resistance training, and it is likely that the neuromuscular characteristics which contributed to higher amounts of CMJ PF also contributed to superior performance in +100% BW CMJ PV.

Measures of CMJ PF were not significantly correlated with BW CMJ PV in males, but they were significantly correlated in females. This finding may be in support of the 'ceiling' effect proposed by Suchomel et al. (2016), as the males in this study were capable of generating significantly higher amounts of isometric strength than the females. It is possible that the males in this study had achieved a level of strength whereby higher levels of isometric strength would be unrelated to increases in parameters of jumping performance (and particularly CMJ propulsive peak velocity), whereas the females jumping performance may still have been affected by increases in isometric strength. Additionally, Rice et al. (2017) suggest that males

demonstrate a superior ability to utilize the SSC due to greater MTU stiffness and therefore could potentially perform better in jumping tasks due to factors that are not associated with CMJ PF. In addition to the difference in strength performance between males and females in the present study, this finding may suggest that measures of maximal CMJ PF are more associated to peak jumping velocity in females than in males.

It is interesting that measures of CMJ PF were not significantly correlated with +100% BW CMJ PV in males, but they were significantly correlated in females. It is possible that, since the males in this study were capable of generating higher amounts of CMJ PF, jumping performance was less dependent on high amounts of maximal force generation due to a 'ceiling' effect proposed by Suchomel et al. (2016).

There were significant correlations between CMJ PF and BW CMJ PV in the stronger and weaker groups. The finding that CMJ PF is associated with higher BW CMJ PV has been contested in the literature, with Thomas, Jones, Rothwell et al. (2015) indicating that higher CMJ PF was associated with lower CMJ PV in weaker participants, although it is admitted that this may be due in part to the homogeneity between subjects in the aforementioned study. It is possible that higher CMJ PF being associated with lower peak velocity in the CMJ in the previously mentioned study could be a result of subjects jumping strategy, as a greater countermovement depth has been related to lower CMJ PV and greater CMJ PF due to the longer time for force-development in the propulsive phase of the jump (Gajewski, Michalski, Buśko, Mazur-Różycka, & Staniak, 2018). It is interesting that the correlation between CMJ PF and BW CMJ PV was similar in both stronger and weaker participants, which suggests that factors other than maximal CMJ PF contributed to jumping peak propulsive velocity including jump

strategy, RFD, activation and synchronization of motor units, intersegmental co-ordination, and dynamic joint stability (Martínez-Cava et al., 2018).

4.8 Differences in performance parameters between sexes. There were significant differences between measures of isometric peak force, ballistic peak force, CMJ PV (loaded and unloaded), and F-v profile slope between males and females in this study, with males producing significantly higher values in all measures of strength and jumping performance parameters. This is not surprising, as males have extensively been reported to produce higher performance parameters in strength testing (Jones et al., 2016; Rice et al., 2017). Contributing factors to these differences may be differences in muscle fibre size (Rice et al., 2017), kinetics, neuromuscular control, higher RFD, muscle fascicle length (Márquez et al., 2017), and fibre-type distribution favouring Type II fibres in males (Rice et al., 2017). Males have also been reported to generate higher amounts of relative peak power (Rice et al., 2017) and jump heights through a range of different jumping methods (Laffaye et al., 2014). Males have also historically shown a superior ability to utilize the SSC in jumping tasks and to withstand greater stretch loads, which is correlated with greater MTU stiffness and enhanced jumping performance (Rice et al., 2017). The findings of this study support the body of evidence that males produce higher levels of maximal strength and higher parameters of jumping performance than their female counterparts.

4.9 Differences in performance parameters between strength groups. There were significant differences in all measured variables between stronger and weaker participants, with the exception of F-v profile slope. In regards to the difference between IMTP and CMJ PF, there are reports in the literature that stronger participants tend to produce higher amounts of CMJ PF (Thomas, Jones, Rothwell, et al., 2015) and vertical jump peak velocity and CMJ height (Khamoui et al., 2011; Thomas, Jones, Rothwell, et al., 2015; West et al., 2011) which suggests

that stronger athletes have a greater ability to generate concentric force and impulse which leads to improved jumping performance. In the present study, the positive correlations between IMTP PF and CMJ PF, CMJ BW PV, and +100% BW CMJ PV may suggest that higher amounts of IMTP PF are related to force and peak velocity attained in an unloaded CMJ as well as peak velocity in a loaded CMJ.

4.10 Limitations of the current study. One limitation for this study is that fat-free mass was not assessed and rather total body mass was used for the calculation of relative strength, and therefore used to stratify groups by strength. Previous researchers have used fat-free mass when normalizing measures of strength and power, however the assessment of fat-free mass was not used in this study. This may have affected the division of subjects into 'stronger' and 'weaker' groups and confounded the results of which subjects fell into each group.

Another potential limitation of this study is that the researchers were unable to control for the type of resistance training that the participants were involved in prior to this study. Exercise programs that trained the movement patterns used in the testing protocols may have influenced the participant's performance ability during the tests. Experience with more jump training, heavy load ballistic exercises, or isometric training protocols may have caused participants to be more efficacious in one test over the other (i.e. a subject with experience in loaded ballistic training but no isometric training may have been better to maximize their performance during the F-v profile protocol over the DSI protocol).

A third limitation of this study may have been the sample sizes used to evaluate correlations once the sample was split into smaller cohorts for sex-based and strength-based analyses. While the sample size was selected to ensure statistical power when analyzing all subjects, the smaller samples used to evaluate correlations in the sex-groups (n=46), and strength

groups (n=46), as well as when sex-groups were further stratified by strength (n=29 for females, n=14 for males) it is possible that the samples in the smaller cohorts were not large enough to successfully identify statistically significant correlations.

The testing protocols selected for this study may in fact have been one of the weaknesses of the study design. In the present study the F-v protocol used involved ballistic movements, whereas the DSI is intended to interpret expressions of muscular strength. For this reason traditional strength-based barbell exercises to assess the lower body F-v profile (e.g. back squat) may have been more appropriate. Additionally, it has been shown that test selection should be specific to the performance parameter characteristics that are being investigated. The biomechanical differences between the IMTP as a means to evaluate muscular strength and the loaded CMJ may have influenced the results of this study.

CONCLUSION

In conclusion, the primary finding of this investigation is that the DSI is not correlated to measures of the lower body F-v profile slope. This is possibly due to biomechanical and neuromuscular performance differences between the testing protocols, and in particular the difference between qualities of isometric and dynamic muscular performance. Similarly, performance parameters of the DSI do not have any significant correlations with the F-v profile slope, and vice-versa. Secondary findings suggest that measures of isometric and ballistic peak force are significantly correlated to CMJ PV across a series of different loading conditions. Tertiary findings support the body of evidence that suggests that males produce higher performance parameters than females in measures of isometric strength, ballistic strength, CMJ PV, and F-v profile slope, but not DSI (which may be explained by strength differences between the cohorts). Finally, the findings confirm that the ability to generate high amounts of isometric strength is likely beneficial for athletic performance, as stronger individuals produce higher ballistic performance parameters (e.g. PF and PV) than their weaker counterparts. This finding also supports research which suggests that individuals with lower DSI values tend to be able to generate higher amounts of isometric strength. These findings are applicable for strength and conditioning practitioners to make informed decisions regarding application of testing protocols for athletic populations.

5.1 Suggestions for future research. Future research may want to address the relationship between the DSI and the F-v profile across the entire range of an individual's ability to generate force. The purpose of this study was to determine if a relatively non-invasive method of evaluating the lower-body F-v profile had any correlation to the results of a DSI assessment commonly viewed as a non-invasive means of strength profile assessment. For this reason, sub-

maximal and relatively light loading conditions were chosen for the protocol to evaluate the F-v profile. It is possible that the loads selected for the present study's evaluation of the F-v profile were not broad enough to fully represent the full spectrum of the participant's force and velocity production characteristics. As such, selecting a broader range of loading conditions may reveal a relationship between the lower-body F-v profile and the DSI.

Future research may also want to evaluate the possibility of a correlation between the DSI and the F-v profile of a more biomechanically similar exercise. It has been shown that the biomechanical characteristics of testing protocols are important to consider when selecting testing batteries. It is possible that the movements used for the DSI, and in particular the IMTP, may be too dissimilar from the CMJ for the results of comparative tests to be correlated. As the IMTP is selected to closely resemble the 2nd pull of Olympic weightlifting movements, it may be pertinent to compare the DSI with the results of a lower-body F-v profile composed evaluated from the 2nd pull of an Olympic weightlifting movement, or from a weightlifting movement derivative.

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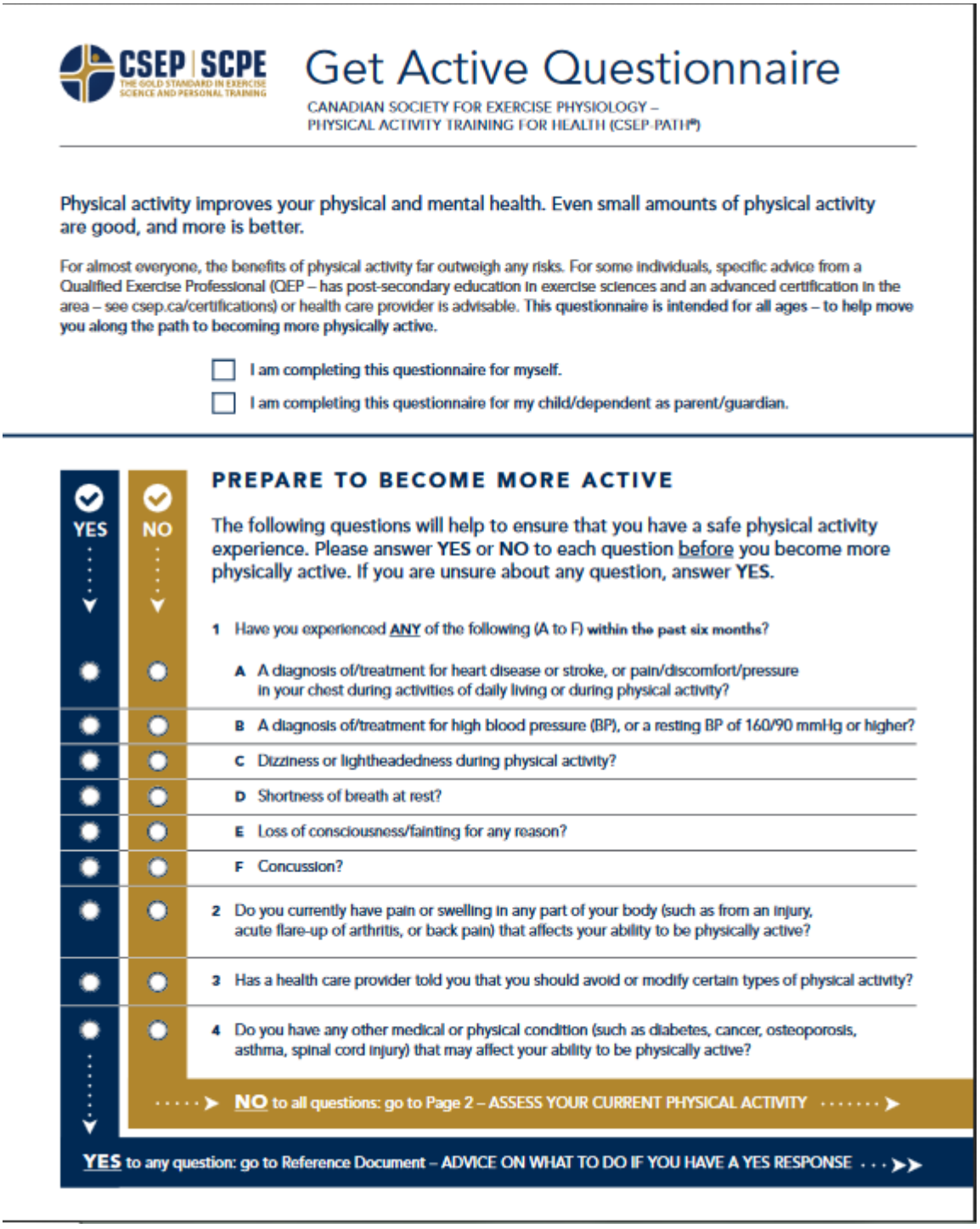
APPENDIX A - Get Active Questionnaire



CSEP | SCPE
THE GOLD STANDARD IN EXERCISE SCIENCE AND PERSONAL TRAINING

Get Active Questionnaire

CANADIAN SOCIETY FOR EXERCISE PHYSIOLOGY –
PHYSICAL ACTIVITY TRAINING FOR HEALTH (CSEP-PATH®)

Physical activity improves your physical and mental health. Even small amounts of physical activity are good, and more is better.

For almost everyone, the benefits of physical activity far outweigh any risks. For some individuals, specific advice from a Qualified Exercise Professional (QEP – has post-secondary education in exercise sciences and an advanced certification in the area – see csep.ca/certifications) or health care provider is advisable. This questionnaire is intended for all ages – to help move you along the path to becoming more physically active.

☐ I am completing this questionnaire for myself.

☐ I am completing this questionnaire for my child/dependent as parent/guardian.

PREPARE TO BECOME MORE ACTIVE

The following questions will help to ensure that you have a safe physical activity experience. Please answer **YES** or **NO** to each question before you become more physically active. If you are unsure about any question, answer **YES**.

YES	NO	
		1 Have you experienced **ANY** of the following (A to F) **within the past six months**?
○	○	**A** A diagnosis of/treatment for heart disease or stroke, or pain/discomfort/pressure in your chest during activities of daily living or during physical activity?
○	○	**B** A diagnosis of/treatment for high blood pressure (BP), or a resting BP of 160/90 mmHg or higher?
○	○	**C** Dizziness or lightheadedness during physical activity?
○	○	**D** Shortness of breath at rest?
○	○	**E** Loss of consciousness/fainting for any reason?
○	○	**F** Concussion?
○	○	2 Do you currently have pain or swelling in any part of your body (such as from an injury, acute flare-up of arthritis, or back pain) that affects your ability to be physically active?
○	○	3 Has a health care provider told you that you should avoid or modify certain types of physical activity?
○	○	4 Do you have any other medical or physical condition (such as diabetes, cancer, osteoporosis, asthma, spinal cord injury) that may affect your ability to be physically active?

➤ **NO** to all questions: go to Page 2 – ASSESS YOUR CURRENT PHYSICAL ACTIVITY ➤

YES to any question: go to Reference Document – ADVICE ON WHAT TO DO IF YOU HAVE A YES RESPONSE ➤➤

CSEP | SCPE
THE GOLD STANDARD IN EXERCISE SCIENCE AND PERSONAL TRAINING

Get Active Questionnaire

ASSESS YOUR CURRENT PHYSICAL ACTIVITY

Answer the following questions to assess how active you are now.

1 During a typical week, on how many days do you do moderate- to vigorous-intensity aerobic physical activity (such as brisk walking, cycling or jogging)? ☐ DAYS/WEEK

2 On days that you do at least moderate-intensity aerobic physical activity (e.g., brisk walking), for how many minutes do you do this activity? ☐ MINUTES/DAY

For adults, please multiply your average number of days/week by the average number of minutes/day: ☐ MINUTES/WEEK

Canadian Physical Activity Guidelines recommend that adults accumulate at least 150 minutes of moderate- to vigorous-intensity physical activity per week. For children and youth, at least 60 minutes daily is recommended. Strengthening muscles and bones at least two times per week for adults, and three times per week for children and youth, is also recommended (see csep.ca/guidelines).

GENERAL ADVICE FOR BECOMING MORE ACTIVE

Increase your physical activity gradually so that you have a positive experience. Build physical activities that you enjoy into your day (e.g., take a walk with a friend, ride your bike to school or work) and reduce your sedentary behaviour (e.g., prolonged sitting).

If you want to do **vigorous-intensity physical activity** (i.e., physical activity at an intensity that makes it hard to carry on a conversation), and you do not meet minimum physical activity recommendations noted above, consult a Qualified Exercise Professional (QEP) beforehand. This can help ensure that your physical activity is safe and suitable for your circumstances.

Physical activity is also an important part of a healthy pregnancy.

Delay becoming more active if you are not feeling well because of a temporary illness.

DECLARATION

To the best of my knowledge, all of the information I have supplied on this questionnaire is correct.
If my health changes, I will complete this questionnaire again.

I answered NO to all questions on Page 1

Sign and date the Declaration below

I answered YES to any question on Page 1

Check the box below that applies to you:

☐ I have consulted a health care provider or Qualified Exercise Professional (QEP) who has recommended that I become more physically active.

☐ I am comfortable with becoming more physically active on my own without consulting a health care provider or QEP.

Name (+ Name of Parent/Guardian if applicable) (Please print)	Signature (or Signature of Parent/Guardian if applicable)	Date of Birth

Date	Email (optional)	Telephone (optional)

With planning and support you can enjoy the benefits of becoming more physically active. A QEP can help.

☐ Check this box if you would like to consult a QEP about becoming more physically active.
(This completed questionnaire will help the QEP get to know you and understand your needs.)

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APPENDIX B – Warmup protocols

5 minutes on the stationary bicycle

CMJ 3 x 3 at 50%, 70%, 90% perceived maximal effort

Back squat at 4 x 2 at 25%, 50%, 75%, 100% bodyweight

Rationale

5 minutes cycling on a stationary bicycle will increase body temperature, which has been shown to increase performance in power (dynamic) tasks (McGowan et al., 2015).

Warm ups consisting of CMJs and back squats of various submaximal loads have been shown to increase performance in subsequent speed and power tasks (McGowan et al., 2015).

APPENDIX C – Familiarization session scoring sheet

Participant Code:	
Session Date and Time:	

Demographic:

1) What is your birth date?

2) What is your biological sex?

3) With which sport do you identify as an athlete?

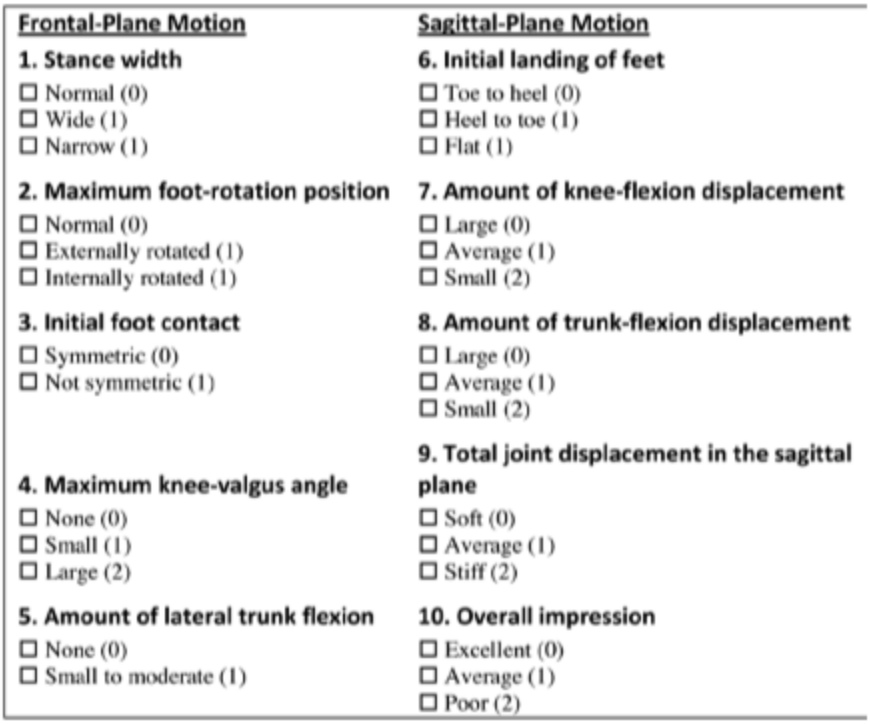
4) What is the highest level of sport that you have competed in?

5) How long have you been playing sports?

6) How long have you been resistance training (2x/week minimal)?

Anthropometric:

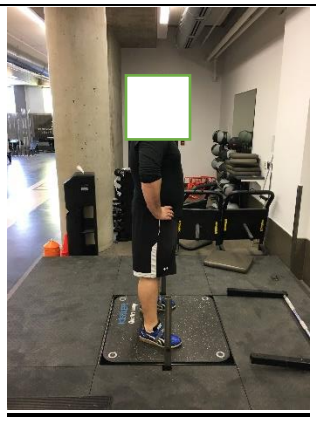
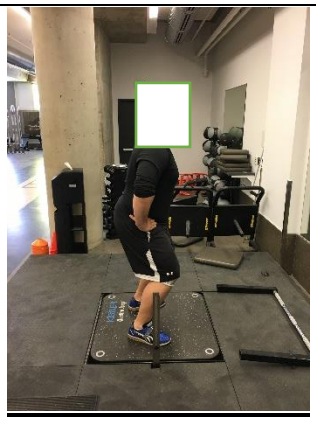
	Measurement 1	**Measurement 2**	**Measurement 3**
Total Height (m):			
Leg Length (m):	L: R:	L: R:	L: R:
Left Thigh Girth (m)	L: R:	L: R:	L: R:



Frontal-Plane Motion	Sagittal-Plane Motion
1. Stance width	**6. Initial landing of feet**
☐ Normal (0)	☐ Toe to heel (0)
☐ Wide (1)	☐ Heel to toe (1)
☐ Narrow (1)	☐ Flat (1)
2. Maximum foot-rotation position	**7. Amount of knee-flexion displacement**
☐ Normal (0)	☐ Large (0)
☐ Externally rotated (1)	☐ Average (1)
☐ Internally rotated (1)	☐ Small (2)
3. Initial foot contact	**8. Amount of trunk-flexion displacement**
☐ Symmetric (0)	☐ Large (0)
☐ Not symmetric (1)	☐ Average (1)
	☐ Small (2)
4. Maximum knee-valgus angle	**9. Total joint displacement in the sagittal plane**
☐ None (0)	☐ Soft (0)
☐ Small (1)	☐ Average (1)
☐ Large (2)	☐ Stiff (2)
5. Amount of lateral trunk flexion	**10. Overall impression**
☐ None (0)	☐ Excellent (0)
☐ Small to moderate (1)	☐ Average (1)
	☐ Poor (2)

Figure 2 — Scoring sheet for the Landing Error Scoring System-Real Time (LESS-RT) assessment tool.

APPENDIX D – DSI Assessment: CMJ

	Subject standing on the force platform with hands on hips.
	Subject in the ‘low’ position of the CMJ. This is the self-selected depth that the subject feels that they can maximize height.

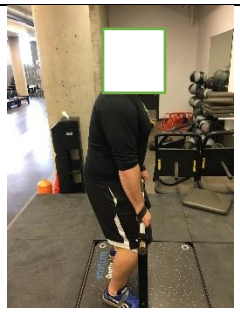
APPENDIX E: Specific details of goniometer use

IMTP hip and knee joint angles were measured by a handheld goniometer following the following instructions:

1) Align the fulcrum of the device with the fulcrum of the joint to be measured.
2) Align the stationary arm of the device with the limb being measured
3) Hold the arms of the goniometer in place while the joint is moved through its range of motion

The use of the goniometer was informed by (Luttgens & Hamilton, 1997)

APPENDIX F – DSI Assessment: IMTP

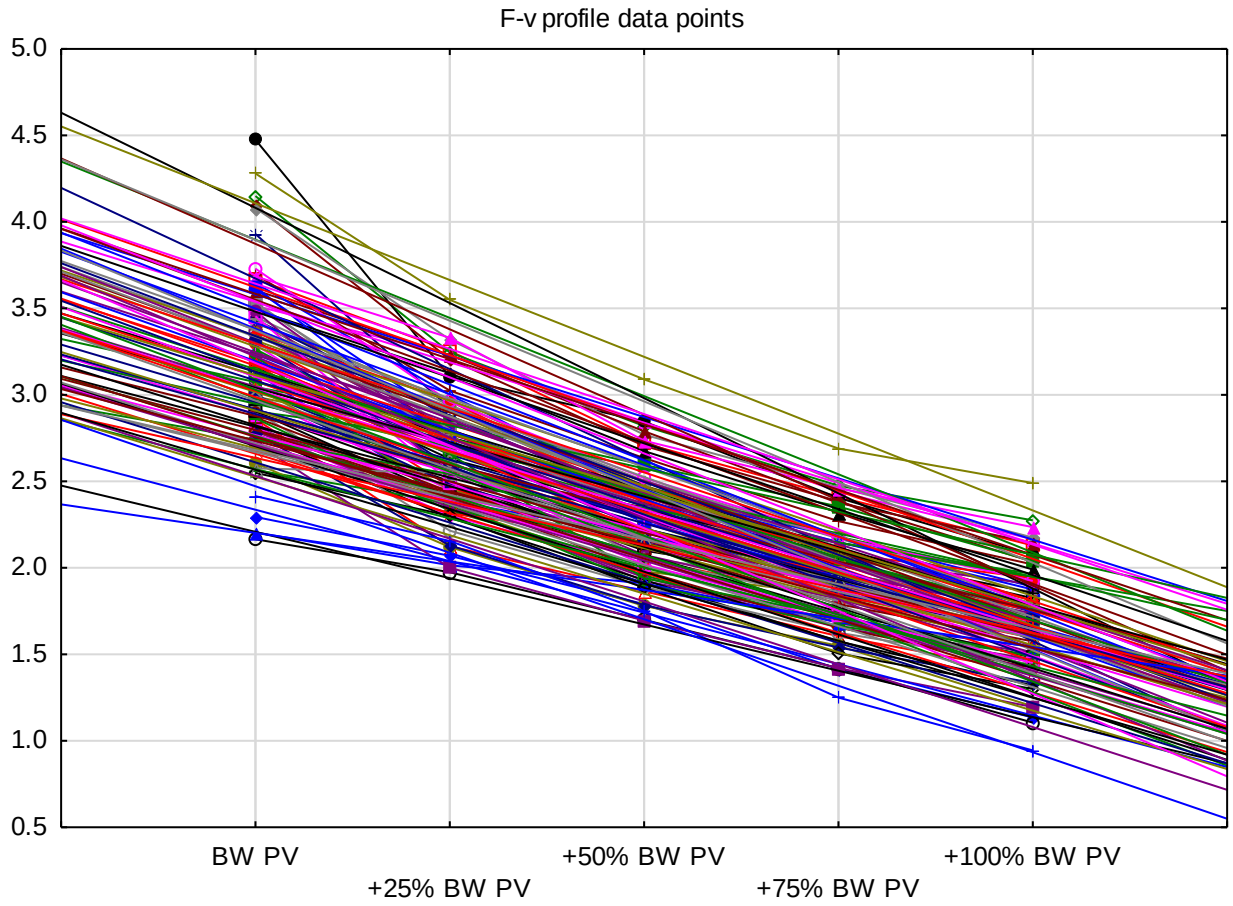
	Subject is attached to the bar using standard lifting straps
	Subject self-selects hip and knee angles to their preferred position for the IMTP.

APPENDIX G – Loaded CMJ F-v profile

	GymAware PowerTool5
	Subject in position with dowel (0.5kg) for unloaded jump (lateral view).
	Subject in position with 1st loading condition at 25% of bodyweight (posterior view).

	Subject in position with 2nd loading condition at 50% of bodyweight (lateral view)
	Subject in position with 3rd loading condition at 75% of bodyweight (posterior view).
	Subject in position with 4th loading condition at 100% of bodyweight (lateral view).

Appendix H



This graph represents all of the F-v profile data points including lines of best fit for each case.