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The Relationship between Components of the Dynamic Strength Index and the Slope of the Force-Velocity Profile in the Loaded Countermovement Jump in Resistance-Trained Males and Females

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ABSTRACT

The purpose of this study was to evaluate the relationship between the dynamic strength index (DSI) and the lower-body Force-velocity (F-v) profile. Eighty-six (n = 58 females) resistance-trained individuals were recruited to perform both the DSI and F-v profile testing protocols to evaluate this relationship, as well as relationships between the components that comprise each test. Spearman 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 (r_s = 0.01; p > 0.05) were found between the DSI value and the F-v profile slope. Significant correlations were found between the DSI and CMJ/IMTP PF (r_s range = -0.63 to 0.22; p < 0.05) and between CMJ/IMTP PF and measures of CMJ PV (r_s range = 0.45 to 0.73; p < 0.05) across the loading conditions. Results suggest that the DSI is not correlated to the F-v profile slope. Two different means of evaluating muscular force in athletes are not correlated; we suggest that athletes require specific evaluations for specific performance characteristics when assessing muscular force.

Keywords: strength measures, countermovement jump, peak force, Force-velocity (F-v) profile.

INTRODUCTION

High levels of muscular strength underpin performance in numerous athletic tasks (Comfort et al. 2017) including performance in throwing, running, and jumping (Suchomel et al. 2016). Research has shown that high amounts of force generation in a short amount of time are important to many sport specific and dynamic tasks (Dos'Santos et al. 2016). This has led exercise professionals to develop training programs to maximize specifically desired characteristics of muscular strength.

Resistance training is a critical stimulus for inducing changes in skeletal muscle size, strength, and power (Jovanovic and Flanagan 2014), with individualized training programs having a higher impact on specific task performance than generic strength training programs (Jiménez-Reyes et al. 2017). Establishing a means of measuring muscular strength is an essential component of monitoring the effectiveness of strength training programs and is sometimes called a strength diagnosis - which refers to the assessment of an athlete's current strength level, aiding the creation and development of athlete profiling (Tidow 1990). 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) (Suchomel et al. 2016). Despite the popularity of this direct method, several problems have been identified with its use, 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 it's impracticality for testing with larger group sizes (Jovanovic and Flanagan 2014). For these reasons the direct method has been contraindicated in some populations such as younger or inexperienced athletes. Beyond these issues, the advent of long-term athlete development and earlier specialization has driven the need for less invasive means of evaluating strength characteristics (McKay et al. 2016).

The use of force platforms to measure muscle force is considered the gold standard for force data collection (Cronin et al. 2004; García-Ramos et al. 2015; Jiménez-Reyes et al. 2017) and has become popular among strength and conditioning practitioners. In particular, measurements of isometric strength may be related to dynamic performance characteristics such as 1RM tests, acceleration ability, and vertical jump ability (McGuigan et al. 2006; Thomas et al. 2015a; Wang et al. 2016; Dos'Santos et al. 2017). Despite their popularity, issues associated with force platform use include sensitivity to extraneous vibration and the high costs that render them outside of the budget for many exercise facilities (Cronin et al. 2004; García-Ramos et al. 2015). This has led to a proliferation of other technologies in the marketplace that can be used 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).

Force platforms and linear position transducers can both be used to evaluate characteristics of strength performance that guide training programs for individual athletes. When evaluated on a force platform, the Dynamic Strength Index (DSI) examines the 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 (Thomas et al. 2015a; Comfort et al. 2017). Alternatively, the F-v relationship (Cronin et al. 2003; Jovanovic and Flanagan 2014; Giroux et al. 2015; Harry G. Banyard et al. 2017) allows linear position transducers to be used to establish an exercise specific Force-velocity (F-v) profile (Bosquet et al. 2010; Jovanovic and Flanagan 2014; García-Ramos et al. 2016) for an athlete.

Both the DSI and the F-v profile can be used to develop/implement strength training programs which favour ballistic movements or maximal strength exercises, in an attempt to maximize the desired outcomes for athletic performance (Sheppard et al. 2008; Samozino et al. 2014; Thomas et al. 2015a; Jiménez-Reyes et al. 2017).

While the slope of the F-v relationship helps to guide exercise professionals when implementing individualized training programs that focus on maximal strength development or on the development of ballistic characteristics, to the authors' knowledge there is no research regarding numeric values of the slope that guide training decisions. The purpose of this cross-sectional correlational study was to determine if a relationship exists between established values of the DSI (Thomas et al. 2015a; Comfort et al. 2017) and the slope of the F-v relationship in a resistance-trained population of males and females. Our primary hypothesis was that the values of the DSI would be significantly correlated to the slope of a F-v lower body profile. Our rationale for this hypothesis is that both tests evaluate similar muscular performance characteristics which can be used to guide subsequent training. As such, we anticipated a relationship between the results.

METHODS

Participants

A total of 86 participants (n=58 women and n=28 men) were representative of a sample of convenience that was recruited primarily from the varsity athlete population at a local Canadian university. The study was open to both male and female athletes who were at least 18 years of age and had completed a minimum of two consecutive months of regular resistance exercise training (two times per week minimum) prior to participation in the study. Participants were deemed ineligible if they had a recent history of musculoskeletal injury or medical condition that prevented them from participating in resistance training exercise. All participants provided informed consent prior to initiating participation, and the study was approved by the host institution's Research Ethics Board (protocol: HS21903).

Experimental Design

The current study used a cross-sectional correlational design. Participants were asked to come to the testing centre on two separate occasions - first to perform a brief familiarization session of the testing protocols, and then a subsequent evaluation session to perform approximately 1.5 hours of testing. Both sessions began with a standardized warm-up routine consisting of 5-minutes of ergometer cycling at a self-selected pace followed by a standardized dynamic warm-up specific to the testing protocols (McGowan et al. 2015). During the familiarization session, demographic and anthropometric information (height and body mass) were collected and participants were evaluated using the Landing Error Scoring System Real-Time (LESS RT) (Padua et al. 2011). There were four jumping trials completed for the LESS-RT. Participants jumped forward off a 30 cm high box to a target landing area situated 50% of their standing height away and then immediately jumped upwards as high as possible from this targeted landing area. Participants were evaluated on Trials 1 and 2 with scoring from the front 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 the trials of the jump landing task. Participants were scored on a 10-item checklist that addressed each of these movements, and a final composite score was calculated by summing all the items on the LESS-RT. If participants scored 5 or above on the LESS-RT, they were excluded from the study due to high potential for musculoskeletal injury (Padua et al. 2011). Participants then performed single sub-maximal effort attempts of the protocols for DSI evaluation and lower body F-v profile evaluation. During the evaluation session, participants completed the same protocol at maximal effort to determine the DSI from the countermovement jump peak force (CMJ PF)/isometric mid-thigh pull peak force (IMTP-PF) and the lower body F-v profile from a series of unloaded and loaded CMJ's. The order of the testing protocol was randomly assigned, and a 5-minute rest period was observed between DSI and lower body F-v profile testing protocols.

Countermovement Jump Peak Force (CMJ PF) Assessment

Immediately following force plate calibration, participants' mass was calculated by having them stand on the force plate platform. The sampling frequency of the force platform was 500 Hz based on previous methodologies that used the same frequency Participants were then 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. Participants performed three jumps, with 30 seconds of rest occurring between (Pereira et al. 2008; Cuk et al. 2016). The peak force for the propulsive phase of the CMJ was determined by visual inspection of the force-time curve (Hori et al. 2009; Cuk et al. 2014, 2016; Comfort et al. 2017) with maximal force being defined as the highest force (excluding body weight) attained prior to jump take-off (Comfort et al. 2017). The average of the two best trials of the three jumps (determined by maximal peak force) was used in the calculation of absolute and relative CMJ PF. Absolute CMJ PF was determined by subtracting the subject's 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).

Isometric Mid-Thigh Pull Peak Force (IMTP PF) assessment

Using the same force platform as was used for CMJ testing, participants were asked to adopt a posture at which they would start the second pull phase of the clean exercise (Comfort et al. 2017). Hip flexion angles between 124-175 degrees and knee angles between 120-150 degrees were allowed as per previous research (Comfort et al. 2017; Brady et al. 2018), with participants encouraged to assume a position as close to 130-150 degrees of knee flexion and 145 degrees of hip flexion as possible in order to maximize force output (Brady et al. 2018). 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 then strapped to the bar using standard lifting straps (Comfort et al. 2017), they 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 would 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 et al. 2017), with participants being given strong verbal encouragement for each trial. A 2-minute rest period occurred between each trial (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 calculated by dividing the absolute IMTP PF score by the participant's own body mass. Absolute IMTP PF was used for calculation of the DSI (Haff et al. 1997, 2005; Comfort et al. 2017).

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. DSI was determined by calculating 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.

Lower body Force-velocity profile assessment

Participants used DHS standard Olympic barbells (15 or 20kg) and DHS brand Olympic bumper plates (sizes of 0.5kg, 1kg, 1.5kg, 2kg, 2.5kg, 5kg, 10kg, 15kg, 20kg, and 25kg) to perform 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). A 1-minute rest period was provided between each CMJ, with 2 minutes provided between each load (Nibali et al. 2013). The placement of the drawstring encoder put the PowerTool5 so that it was vertically under the path of the lift. Peak velocity data during the CMJ trials was captured using GymAware PowerTool5 software (Kinetic Performance Technology Pty. Ltd., 8/26-28 Winchcombe Ct, Canberra ACT 2602). Peak velocity data was hand-written onto a recording sheet and subsequently entered on a customized Excel spreadsheet for computation of 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 and Flanagan 2014).

Statistical Analyses

Statistical analysis was completed using Statistica software (Tibco Statistica 13.3, TIBCO Software Inc., 3307 Hillview Avenue, Palo Alto, CA, U.S.A.). 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 for all the variables. 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. Correlations were set 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). Statistical significance was set at $p \leq 0.05$.

RESULTS

A total of 106 athletes were recruited to the study, with 86 participants (58 female and 28 male) completing the entire study protocol. Demographic data indicated that participants came from a wide variety of athletic backgrounds and possessed wide ranging levels of experience in competitive sport. Descriptive characteristics of all participants and broken down by biological sex are listed in Table 1.

Spearman Rank Correlation Results

Spearman correlations indicated that there was little relationship ($r_s = 0.01$; $p > 0.05$) between the DSI and the F-v slope. However, further sub-analysis (see Table 2) did identify several significant correlations ($p \leq 0.05$) between the different methods of strength assessment that ranked from small to very large correlations according to the scoring system used in this study. Partial correlations did exist when controlling for mass and were deemed significant at $p \leq 0.05$ with a 90% CI (see Table 3). Generally, the Spearman correlation comparing the DSI to F-v slope was not significant when controlling for body mass ($r_s = 0.06$; $p > 0.05$); however, there were several significant correlations when evaluating the strength assessment methods in relation to one another (see Table 3) ranging from small to nearly perfect correlations according to the scoring system used in this study.

Table 1. Descriptive characteristics

Variable	Males (n=28)	Females (n = 58)	All (n=86)
Height (m)	1.82 ± 0.07 (1.70 - 2.00)	1.68 ± 0.07 (1.56 - 1.85)	1.72 ± 0.10 (1.56 - 2.00)
Mass (kg)	91.2 ± 16.2 (65.6 – 143.8)	66.3 ± 8.7 (50.8 – 102.5)	74.4 ± 16.5 (50.8 – 143.8)
Age (years)	23.4 ± 3.2 (18.7 – 29.9)	22.3 ± 3.0 (18.1 – 30.6)	22.7 ± 3.1 (18.1 – 30.6)
LESS Real Time score	1.93 ± 1.40 (0 – 4)	2.10 ± 1.28 (0 – 4)	2.05 ± 1.30 (0 – 4)
Years in sport	14.6 ± 5.4 (2.0 – 25.0)	14.8 ± 5.2 (0.0 – 25.0)	14.7 ± 5.3 (0.0 – 25.0)
Years in RT	7.1 ± 3.4 (3.0 – 15.0)	4.4 ± 2.9 (0.2 – 16.0)	5.3 ± 3.3 (0.2 – 16.0)
Leg length (m)	1.03 ± 0.06 (0.89 – 1.17)	0.99 ± 0.08 (0.89 – 1.33)	1.00 ± 0.08 (0.88 – 1.33)
Thigh girth (m)	0.60 ± 0.06 (0.48 – 0.81)	0.57 ± 0.04 (0.51 – 0.70)	0.58 ± 0.05 (0.48 - 0.81)

Note: Data reported with Mean ± SD and (minimum – maximum) below mean and SD. Note: LESS = landing error scoring system; RT=resistance training

Table 2. Spearman rank order correlations (all participants)

	A. IMTP PF	R. IMTP PF	A. CMJ PF	R. CMJ PF	BW PV	+100% BW PV	DSI	F-v 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 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.*

Table 3. Partial correlations controlling for mass (relative values)

	A. IMTP PF	R. IMTP PF	A. CMJ PF	R. CMJ PF	BW PV	+100% BW PV	DSI	F-v 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 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.*

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, and therefore did not support the primary hypothesis of this investigation. We anticipated that the two tests would be correlated since they are evaluating similar methods for guiding training purposes (i.e., more velocity focused or more strength focused training parameters). The secondary results of this study indicate that measures of ballistic and isometric peak force are correlated to measures of CMJ PV across a series of loading conditions. 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.

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. Previous research has suggested that the biomechanical differences between the IMTP and the CMJ, including the types of muscular contraction involved may mean that some measures of IMTP performance are unrelated to CMJ performance across a series of different loading conditions (Thomas et al. 2015a). It has been suggested that testing protocols are most effective when considering the biomechanical characteristics of the involved protocols (Thomas et al. 2015a; Brady et al. 2018). Moreover, the importance of task-specificity when it comes to assessing measures of explosive muscular performance is key when assessing performance parameters (Morales-Artacho et al. 2018).

One potential difference between the testing protocols may have been the differences in joint angles necessary to perform the IMTP versus the CMJ. Because of the length-tension and F-v relationships of skeletal muscle, maximal voluntary torque around a joint is dependent on the angle of the joint and angular velocity around a joint (Tillin et al. 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 a statistically significant relationship between testing protocols. 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 et al. 2016). The patterns that are associated with the CMJ that can be changed with additional loading may affect the development of maximal force, rate of force development, the activation and synchronization of motor units, and dynamic joint stability (Martínez-Cava et al. 2018), with a change in these variables likely affecting performance parameters.

There are inherent differences between isometric and dynamic activity that may also have influenced the relationship between the results of the testing protocols. Research has suggested that the validity of isometric tests to correlate with performance in dynamic activity can be called into question because isometric tests are not specific to the dynamic movement patterns associated with human performance (45). Additionally, performance in jumping tasks is determined by both the force generated and the 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 et al. 2015b).

The literature suggests that the F-v profile slope may be more dependent on actual strength performance than the DSI. Research by Comfort et al. (Comfort et al. 2018) demonstrated 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 et al. 2015a), but instead reflects how the individual expressed force during the testing protocol that they participated in (McMahon et al. 2017). As such, the DSI should not be used as a means of comparing different individuals. However, the F-v profile has been recommended by some researchers as a means of comparing performance in resistance training exercise between individuals (Jovanovic and Flanagan 2014), and thus 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.

When controlling for mass, our results indicated that 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 due to the confounding effect of body size 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 et al. 2015b) this finding supports previous research which suggests 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. Khamoui et al. (Khamoui et al. 2011) reported 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, our data indicates that the IMTP PF did not correlate with changes in CMJ PF performance across a range of loading conditions in ballistic lower body exercises.

The absolute values of CMJ PF were correlated with F-v profile slope 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. 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 research which suggests that different individuals possess different F-v characteristics, and that this difference may impact the ability to generate high velocities across different loading conditions (30).

Measures of IMTP PF were significantly negatively correlated to DSI values. This result supports previous research which suggests 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 et al. 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 when controlling for mass. When not controlling for mass, there was no correlation between 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 values 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 and Zolotarjova 2017). A study by Tillin et al. (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 support high levels of ballistic force production would also be favourable for high amounts of isometric force production. However, the ability of an 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 rate of force development). 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 appears that they had a stronger relationship with the DSI value.

This study found that the F-v profile slope was negatively correlated with measures of BW CMJ PV. This finding was corroborated by previous reports that lower F-v slope values are attained by subjects who have higher contraction velocities in the investigated exercises (24). Another study 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 (60). Jovanovic and Flanagan (Jovanovic and 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 are correlations between IMTP PF and CMJ PF. This finding is supported by research that has suggested that measures of isometric strength are correlated with dynamic performance measures. For example, one report identified that IMTP PF is correlated with measures of CMJ PF (57). 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 rate of force development, 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.

Measures of IMTP PF were correlated with measures of BW PV. This finding supports the results by Townsend et al. (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.

Measures of CMJ PF were correlated with BW CMJ PV both with and without controlling for mass. This finding is to be expected, as maximal lower-body strength levels are reflected in many vertical jump performance variables (Sole), 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. (Cormie et al. 2011b) report that individuals who can produce higher amounts of force can generate 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.

One potential limitation of the current study is that fat-free mass was not assessed. Instead, 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. A second limitation of this investigation is that the study design did not control for the type of resistance training that the participants were involved in prior to initiating 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 participant with experience in loaded ballistic training but no isometric training may have better maximized their performance during the F-v profile protocol over the DSI protocol). A further limitation to this study may have been the self-selected squat depth that was used for the progressively loaded CMJ used to determine the F-v profile. While we instructed our participants to execute each CMJ with the various loads using the same degree of flexion for each of the lower body joints, there may have been differences in the degree of flexion that each participant achieved which may have affected our results for this measure.

In conclusion, the primary finding of this investigation is that the DSI measures are unrelated to measures of the lower body F-v profile slope. Secondarily, the results suggest that measures of isometric and ballistic peak force are significantly correlated to CMJ PV across a series of different loading conditions. Therefore, it appears that peak velocity measured with a linear position transducer, over a range of loading patterns, may provide a means to predict the performance of athletic individuals in terms of isometric or ballistic force production on a force-plate and may provide a cost-effective alternative to purchasing a force-plate for strength and conditioning facilities.

These findings are applicable for strength and conditioning practitioners to make informed decisions regarding application of testing protocols for athletic populations. Our study indicated that the type of testing used to determine strength profiles (i.e., DSI versus F-v profile) does not have a relationship. This is important to know for strength and conditioning specialists, as it is likely more appropriate for testing to be done which mimics the related movements that are essential for athletic performance rather than just testing athletes with a test that may not correlate with athletic performance on the field of play. As the IMTP closely resembles the second pull of Olympic weightlifting movements, it may be pertinent to compare the DSI with the results of a lower-body F-v profile evaluated from the second pull of an Olympic weightlifting movement, or from a weightlifting movement derivative.

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