An Investigation Into the Relationship Between Maximum Isometric Strength and Vertical Jump Performance

Christopher Thomas,[1] Paul A. Jones,[1] James Rothwell,[1] Chieh Y. Chiang,[2] and Paul Comfort[1]

[1]*Directorate of Sport, Exercise and Physiotherapy, University of Salford, Salford, Greater Manchester, United Kingdom; and* [2]*Department of Exercise and Sport Science, East Tennessee State University, Johnson City, Tennessee*

Abstract

Thomas, C, Jones, PA, Rothwell, J, Chiang, CY, and Comfort, P. An investigation into the relationship between maximum isometric strength and vertical jump performance. *J Strength Cond Res* 29(8): 2176–2185, 2015—Research has demonstrated a clear relationship between dynamic strength and vertical jump (VJ) performance; however, the relationship of isometric strength and VJ performance has been studied less extensively. The aim of this study was to determine the relationship between isometric strength and performance during the squat jump (SJ) and countermovement jump (CMJ). Twenty-two male collegiate athletes (mean ± *SD*; age = 21.3 ± 2.9 years; height = 175.63 ± 8.23 cm; body mass = 78.06 ± 10.77 kg) performed isometric midthigh pulls (IMTPs) to assess isometric peak force (IPF), maximum rate of force development, and impulse (IMP) (I100, I200, and I300). Force-time data, collected during the VJs, were used to calculate peak velocity, peak force (PF), peak power (PP), and jump height. Absolute IMTP measures of IMP showed the strongest correlations with VJ PF ($r = 0.43$–0.64; $p \leq 0.05$) and VJ PP ($r = 0.38$–0.60; $p \leq 0.05$). No statistical difference was observed in CMJ height (0.33 ± 0.05 m vs. 0.36 ± 0.05 m; $p = 0.19$; ES = −0.29) and SJ height performance (0.29 ± 0.06 m vs. 0.33 ± 0.05 m; $p = 0.14$; ES = −0.34) when comparing stronger to weaker athletes. The results of this study illustrate that absolute IPF and IMP are related to VJ PF and PP but not VJ height. Because stronger athletes did not jump higher than weaker athletes, dynamic strength tests may be more practical methods of assessing the relationships between relative strength levels and dynamic performance in collegiate athletes.

Key Words peak force, peak power, jump height

Address correspondence to Christopher Thomas, c.thomas2@edu.salford.ac.uk.

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Introduction

A number of studies have investigated the relationship between vertical jump performance (VJ), both in the squat jump (SJ) and countermovement jump (CMJ) to strength and power in single-joint isometric tests (2), multijoint isometric tests (14,15), and multijoint dynamic tests (40). Several of the characteristics associated with strength (peak force [PF], rate of force development [RFD], peak velocity [PV], and peak power [PP]) have been identified as underlying mechanisms related to sports performance, particularly in the VJ (30). Success in sport depends on the development of force, power, and impulse (IMP), all of which contribute to VJ performance (2,24,30,38,40). Previous research reported VJ to be a reliable predictor of success in a number of sports, which include ice hockey (4), soccer (39), handball (5), volleyball (28), rugby (13), karate (27), and weightlifting (34). Strong correlations have been found between the 1 repetition maximum (RM) squat (7), isometric peak force (IPF) (31), and PP during the CMJ and SJ (30). Furthermore, training-induced increases in measures of maximum strength have been shown to result in VJ height and power output increases (30).

Studies have used various methods to assess strength including isokinetics (42), machine squats (41), and free-weight squats (26,31) when investigating the relationship between strength and VJ performance. Moderate to strong correlations ($r = 0.54$–0.94) have been observed between free-weight squats and VJ performance (30,39). There can be several explanations for the variations in strength of the relationship between dynamic strength assessment and VJ performance, and these include the method of strength test, scaling of results, determination of VJ performance, and the instruction of the VJ (24). Researchers involved in the testing of lower-body strength have gravitated more toward the traditional free-weight test of maximal strength as typically used in assessing athletes in rugby union (1), American football (12), soccer (39), and volleyball (29). More recently, researchers have started to use variations of the power clean to assess lower-body strength as these exercises have similar characteristics to sporting movements (sprinting, jumping, change of direction [COD]) (18). As a result, weightlifting exercises have been used as a method to test lower-body strength and power among athletes competing in a range of sports (14,18).

Previous literature indicates that isometric measures of maximum strength have only weak-to-moderate correlations with dynamic exercise variables (38). Isometric and dynamic performance assessment differ in biomechanical characteristics such as the type of loading, magnitude of loading, joint ranges of motion, and joint angular velocities, resulting in some training-induced adaptations being reflected in some tests but not others (15,26,32). That is, testing methods that share characteristics of sports performance (e.g., forces, body position, RFD) are required for the appropriate application of testing results to formulate future resistance training program. The 2 most commonly used exercises for isometric strength assessment are the isometric back squat and isometric midthigh pull (IMTP) (15). Early research suggests IPF to correlate well with VJ variables ($r = 0.53$–0.82), such as PF, PP, and jump height in a range of populations such as weightlifting, cycling, recreationally trained, wrestling, American football, and soccer, because of similarities in vertically directed force production and the subsequent biomechanically derived variables. This indicates that the IMTP may be a valid predictor of VJ performance in a variety of athletes and sports (15,19,32).

During the IMTP, a standardized pulling technique has not been determined, with some researchers using a pull from just above the knee and others using a midthigh pull (14,15,19,26,33). Taking this into account, a recent study proposed that knee and hip angles be self-selected by athletes in order for each individual to position themselves in an optimal body position, with the bar at midthigh, replicating the midthigh pull position to produce the highest PF possible (33).

Another common strength measurement during the IMTP is RFD, which has not been as consistent in terms of its reliability and relationship to dynamic performance. Early investigations found RFD to show small to very large significant correlations ($r = -0.18$ to 0.82) with VJ performance when using a sampling window of 2 milliseconds. The results of Haff et al. (14) have been questioned with small nonsignificant correlations observed between RFD and VJ performance ($r = -0.04$ to -0.34) but very large and nearly perfect significant correlations between RFD and VJ PP in elite female weightlifters ($r = 0.88$–0.92), when calculating RFD as the peak RFD through rate of change between 2 adjacent force samples divided by the intersample time interval (2 milliseconds). Haff et al. (15) found small to large nonsignificant correlations, whereas Stone et al. (32) only observed moderate inverse correlations between RFD with sprint cycling performance variables ($r = -0.28$ to -0.39) when using previously established RFD analysis using a 5-millisecond window (31). In a recent study by Beckham et al. (3), RFD was determined using a 5-millisecond window in addition to 100-, 150-, 200-, and 250-millisecond time points, with 0–200 milliseconds observing large significant correlations ($r = 0.58$–0.65) and 0–250 milliseconds large to very large significant correlations with weightlifting performances ($r = 0.58$–0.78). Kraska et al. (20) found RFD to show high reliability when sampling at 10-millisecond windows, showing moderate significant correlations ($r = 0.43$–0.48) to VJ height, and these correlations were extended to large correlations ($r > 0.50$) when measured with weighted VJ performance at 20 kg. Although outside the scope of this investigation, the question remains whether IMTP RFD be determined through a sampling window (e.g., 2, 5, 10, 20 ms) or a specific time window (e.g., 0–50, 0–100, 0–150, and 0–200 ms).

The aim of this study was to determine the relationship between maximal isometric strength variables and measurements of VJ performance, in collegiate athletes. In addition, observations were made to discover whether those athletes who have high performance in isometric strength testing would have high performance in VJ performance measures. It was hypothesized that relationships between maximal isometric strength variables and VJ performance measures would be similar to those previously identified in a similar subject cohort (20,23). In addition, we hypothesized that relatively stronger athletes will perform better in VJ performance measures, specifically VJ PP and VJ height.

Methods

Experimental Approach to the Problem

This study was designed to investigate the relationships between isometric strength (IPF, maximum rate of force development [mRFD], IMP100, I200, I300, and total IMP) and maximal VJ performance (SJ and CMJ PV, PF, PP, and jump height) in collegiate athletes. Maximal isometric strength was selected as it is highly reliable and provides very efficient measures of maximal strength in a variety of populations (15,23,24), whereas SJ and CMJ were selected as these are commonly used to assess VJ performance (26,39).

Athletes were required to abstain from training for 48 hours before testing and asked to maintain a consistent fluid and dietary intake on each day of testing. Before the start of testing, athletes were instructed to perform a standardized warm-up, as directed by the investigator.

Subjects

Twenty-two collegiate male athletes (mean ± *SD*; age = 21.3 ± 2.9 years; height = 175.63 ± 8.23 cm; body mass = 78.06 ± 10.77 kg) active in cricket, judo, rugby, and soccer participated in this investigation. All individuals volunteered for the testing as part of their normal training and monitoring regime. Ethical approval was provided by the institutional review board, and all athletes provided written informed consent. All procedures conformed to the Declaration of Helsinki. All individuals were familiar with testing protocols.

Warm-up Procedures

A standardized warm-up procedure was followed by all athletes before VJ and isometric strength testing. Athletes performed a series of midthigh clean pulls, including 1 set of 5 midthigh clean pulls with an empty barbell (Werksan Olympic Bar, Werksan, Moorestown, NJ, USA) and 3 sets of 3 midthigh clean pulls with 40–100 kg (in an ascending order), based on current training loads. Vertical jumps consisted of 2 types: bodyweight SJ and CMJ. Approximately 1 minute of rest was given between jumps; athletes performed 2 practice jumps, 1 at 50% perceived effort and 1 at 75% perceived effort, for both the SJ and CMJ, before the maximal effort tests began. Before all data collection procedures, the force plate was calibrated using criterion masses.

Vertical Jump Testing

Vertical jump height data were collected using a portable force plate sampling at 600 Hz (400 Series Performance Force Plate; Fitness Technology, Adelaide, Australia). The force plate was interfaced with computer software (Ballistic Measurement System [BMS]) that allows for direct measurement of force-time characteristics and then analyzed using the BMS software. Data were filtered using a fourth-order Butterworth filter with a 16 Hz cutoff frequency. The athletes were familiar with all jumps and explosive exercise, permitting the use of warm-up sets and initial calibration for familiarization with the equipment to ensure reliable jump performances.

Vertical jump tests began with the SJ condition. On stepping onto the force plate, athletes were instructed to get in the "ready position," which consisted of the subject having their hands on hips and assuming a self-selected squat depth. Once in position, a countdown of "3, 2, 1 Jump" was given. A 3-second hold of the bottom position was used to eliminate the involvement of the stretch-shorten cycle (SSC). Force-time data were visually inspected, and any decrease in force >50 N was disallowed, and a further trial was performed after a rest period of 1 minute. Athletes performed 3 trials with 1 minute of rest between trials. On completion of the SJ trials, athletes were provided with a rest period of 3 minutes before performing the CMJ trials.

Countermovement jumps were performed using standard procedures outlined in previous research (15). Countermovement jumps were performed with the hand on the hips, and countermovement depth was self-selected by the athletes to maximize CMJ height. Athletes performed 3 trials, with 1 minute of rest between trials. During the SJ and CMJ, PV, PF, PP, and jump height were all measured during the concentric phases of the SJ and CMJ. The maximum force recorded from the force-time curve during the concentric phase was reported as the PF.

Acceleration due to gravity was subtracted from the calculated acceleration data to ensure that only the acceleration produced by the subject was used to determine velocity. Concentric PV of the center of mass was determined by the product of acceleration and time data at each time point: velocity (v) = Δ in acceleration (a) $\times$ Δ in time

Table 1. Absolute and relative performance variables for strength and power measurements in the IMTP, CMJ, and SJ ($n = 22$).*†

	Absolute		Relative
IMTP			
IPF (N)	2,709.15 ± 586.79	$N \cdot kg^{-1}$	34.56 ± 5.27
mRFD ($N \cdot s^{-1}$)	10,898.77 ± 4,543.11	$N \cdot kg^{-1} \cdot s^{-1}$	137.86 ± 50.54
I100 ($N \cdot s$)	79.38 ± 11.96	$N \cdot kg^{-1} \cdot s$	1.02 ± 0.06
I200 ($N \cdot s$)	157.49 ± 24.02	$N \cdot kg^{-1} \cdot s$	2.02 ± 0.13
I300 ($N \cdot s$)	236.58 ± 35.97	$N \cdot kg^{-1} \cdot s$	3.03 ± 0.21
Total IMP ($N \cdot s$)	10,405.54 ± 2,432.20	$N \cdot kg^{-1} \cdot s$	132.95 ± 24.28
CMJ			
PV ($m \cdot s^{-1}$)	3.07 ± 0.30	$m \cdot s^{-1}$	3.07 ± 0.30
PF (N)	2,106.06 ± 539.24	$N \cdot kg^{-1}$	26.88 ± 5.04
PP (W)	4,890.29 ± 1,277.85	$W \cdot kg^{-1}$	62.56 ± 12.87
Jump height (m)	0.35 ± 0.05	m	0.35 ± 0.05
SJ			
PV ($m \cdot s^{-1}$)	2.69 ± 0.23	$m \cdot s^{-1}$	2.69 ± 0.23
PF (N)	2,091.86 ± 494.94	$N \cdot kg^{-1}$	26.82 ± 4.87
PP (W)	4,325.95 ± 814.15	$W \cdot kg^{-1}$	55.64 ± 8.14
Jump height (m)	0.30 ± 0.05	m	0.30 ± 0.05

*IMTP = isometric midthigh pull; CMJ = countermovement jump; SJ = squat jump; IPF = isometric peak force; mRFD = maximum rate of force development; IMP = impulse; PV = peak velocity; PF = peak force; PP = peak power.
†Values are expressed as mean ± *SD*.

Table 2. Reliability data for IMTP, CMJ, and SJ variables.*

Reliability variable	ICC (90% CI)	%CV (90% CI)	TE	Change in mean (%)
IMTP				
IPF (N)	0.97 (0.94–0.99)	4.2 (3.4–5.7)	109.6	−0.6
mRFD (N·s^{-1})	0.81 (0.65–0.91)	15.1 (12.0–20.9)	2,443.3	5.6
I100 (N·s)	0.87 (0.74–0.93)	6.1 (4.9–8.3)	4.7	−1.6
I200 (N·s)	0.86 (0.74–0.93)	6.2 (5.0–8.5)	9.4	−2.2
I300 (N·s)	0.87 (0.75–0.94)	5.7 (4.6–7.8)	13.4	−2.2
Total impulse (N·s)	0.95 (0.90–0.98)	7.1 (5.7–9.7)	606.6	−1.5
CMJ				
PV (m·s^{-1})	0.73 (0.50–0.85)	5.5 (4.4–7.5)	0.2	1.0
PF (N)	0.98 (0.95–0.99)	4.0 (3.2–5.4)	88.0	−1.2
PP (W)	0.97 (0.95–0.99)	4.8 (3.8–6.5)	216.1	−0.1
Jump height (m)	0.91 (0.83–0.96)	5.1 (4.0–6.9)	0.02	−0.8
SJ				
PV (m·s^{-1})	0.70 (0.45–0.85)	5.5 (4.3–7.6)	0.2	1.3
PF (N)	0.99 (0.97–0.99)	2.9 (2.3–4.0)	58.6	−0.2
PP (W)	0.91 (0.82–0.96)	6.5 (5.1–9.0)	265.3	1.2
Jump height (m)	0.86 (0.72–0.93)	6.8 (5.3–9.4)	0.02	1.6

*IMTP = isometric midthigh pull; CMJ = countermovement jump; SJ = squat jump; ICC = intraclass correlation coefficient; CV = coefficient of variation; CI = confidence intervals; TE = typical error; IPF = isometric peak force; mRFD = maximum rate of force development; PV = peak velocity; PF = peak force; PP = peak power.

(t), where $\Delta a = a_{(i-1)} - a_{(i)}$ and $\Delta t = t_{(i-1)} - t_{(i)}$. Concentric PP was determined as the force multiplied by the velocity. Jump height was calculated from flight time ($1/8\ [g \times t^2]$) (where g = the acceleration due to gravity and t = air time).

Isometric Midthigh Pull Testing

After the VJ tests, athletes were provided with a rest period of approximately 10 minutes before the IMTP test. Isometric midthigh pull testing was performed using a portable force plate sampling at 600 Hz (400 Series Performance Force Plate; Fitness Technology). The force plate was interfaced with computer software (BMS) that allows for direct measurement of force-time characteristics and then analyzed using the BMS software. Data were filtered using a fourth-order Butterworth filter with a 16 Hz cutoff frequency. For the IMTP, athletes obtained self-selected knee and hip

Table 3. Correlations between absolute and relative isometric force-time measures and absolute vertical jump variables.*

Variable	CMJ PV	SJ PV	CMJ PF	SJ PF	CMJ PP	SJ PP	CMJ height	SJ height
IPF	0.05	−0.05	0.45†	0.41	0.34	0.46†	−0.02	−0.04
Relative IPF	0.08	0.03	0.10	0.10	0.01	0.15	−0.09	−0.10
IMTP mRFD	−0.02	0.12	0.04	−0.01	0.07	0.13	0.01	0.13
Relative IMTP mRFD	−0.02	0.13	−0.14	−0.15	−0.08	−0.02	−0.04	0.09
IMTP I100	−0.08	−0.10	0.64‡	0.57‡	0.51†	0.60‡	0.01	−0.07
Relative I100	−0.29	−0.06	0.07	0.09	−0.07	0.04	−0.12	−0.21
IMTP I200	−0.07	−0.12	0.63‡	0.56‡	0.50†	0.59‡	−0.03	−0.08
Relative I200	−0.08	−0.09	0.06	0.09	−0.08	0.03	−0.15	−0.22
IMTP I300	−0.09	−0.12	0.63‡	0.58‡	0.49†	0.60‡	0.01	−0.08
Relative I300	−0.10	−0.08	0.06	0.12	−0.10	0.04	−0.10	−0.20
IMTP total IMP	0.11	−0.30	0.43†	0.50†	0.43†	0.38	0.13	−0.03
Relative IMTP total IMP	0.10	−0.30	0.07	0.19	0.13	0.02	0.06	−0.33

*CMJ = countermovement jump; IPF = isometric peak force; IMTP = isometric midthigh pull; mRFD = maximum rate of force production; SJ = squat jump; IMP = impulse; I100 = impulse 100 ms; I200 = impulse 200 ms; I300 = impulse 300 ms.
†Correlations significant at $p \leq 0.05$.
‡Correlations significant at $p \leq 0.01$.

Table 4. Correlations between SJ variables.*

Variable	SJ PV ($m \cdot s^{-1}$)	Relative SJ PF ($N \cdot kg^{-1}$)	Relative SJ PP ($W \cdot kg^{-1}$)	SJ height (m)
SJ PV ($m \cdot s^{-1}$)	1.00	−0.08	0.47†	0.47†
Relative SJ PF ($N \cdot kg^{-1}$)	−0.08	1.00	0.60‡	0.11
Relative SJ PP ($W \cdot kg^{-1}$)	0.47†	0.60‡	1.00	0.30
SJ height (m)	0.47†	0.11	0.30	1.00

*SJ = squat jump; PV = peak velocity; PF = peak force; PP = peak power.
†Correlations significant at $p \leq 0.05$.
‡Correlations significant at $p \leq 0.01$.

angles based on the reports of previous research. For this test, an immovable bar (Werksan Olympic Bar; Werksan) was positioned at midthigh position, just below the crease of the hip. The bar height could be fixed at various heights above the force platform to accommodate different sized athletes, and the rack was anchored to the floor. Once the bar height was established, the athletes stood on the force platform, and their hands were strapped to the bar in accordance with previously established methods (14,32). Each athlete was provided 2 warm-up pulls, 1 at 50% and 1 at 75% of the athletes perceived maximum effort, separated by 1 minute of rest. Once body position was stabilized (verified by watching the subject and force trace), the subject was given a countdown of "3, 2, 1, Pull." Minimal pretension was allowed to ensure that there was no slack in the subject's body before initiation of the pull. Athletes performed 2–3 maximal IMTP, with the instruction to pull against the bar with maximal effort as quickly as possible; this instruction has been previously found to produce optimal testing results (15,32). Each maximal isometric trial was performed for 5 seconds, and all athletes were given strong verbal encouragement during each trial. One minute of rest was given between the maximal effort pulls. The maximum force recorded from the force-time curve during the 5-second IMTP trial was reported as the IPF. This IPF was also used in the measurement of relative IPF (IPF divided by body mass), which accounts for subject body mass. Maximum RFD was determined by dividing the difference in consecutive vertical force readings by the time interval (0.0017 seconds) between readings (19). Impulse at 100, 200, and 300 milliseconds and total IMP were also calculated. The time intervals were selected based on typical ground contact phases for the various sprint, jump, and COD activities that would be experienced by the athletes used in the investigation (36,37). Previous literature has indicated that scaling forces allometrically appear to control for sex differences between athletes (33); however, recent research suggests both ratio (load divided by body mass) and allometric (load·[body mass × 0.67]) scaling provide effective mean values for normalizing data (9).

Statistical Analyses

Reliability of performance measures was assessed by intraclass correlation coefficient (ICC), coefficient of variation (%CV), typical error (TE), and calculating the relative change in the mean observations. The ICC and relative change in mean observations were determined by a paired *t*-test using SPSS software (version 17.0; SPSS, Inc., IL, USA). The %CV was calculated as 100 × (the *SD* of difference scores/$\sqrt{2}/100$) − 100 by using log-transformed data (16). Typical error was calculated as *SD* of difference scores divided by $\sqrt{2}$. Normality of data was assessed by Shapiro-Wilk's

Table 5. Correlation between relative CMJ variables.*

Variable	CMJ PV ($m \cdot s^{-1}$)	Relative CMJ PF ($N \cdot kg^{-1}$)	Relative CMJ PP ($W \cdot kg^{-1}$)	CMJ height (m)
CMJ PV ($m \cdot s^{-1}$)	1.00	−0.13	0.25	0.52†
Relative CMJ PF ($N \cdot kg^{-1}$)	−0.13	1.00	0.76†	0.17
Relative CMJ PP ($W \cdot kg^{-1}$)	0.25	0.76†	1.00	0.63†
CMJ height (m)	0.52†	0.17	0.64†	1.00

*CMJ = countermovement jump; PV = peak velocity; PF = peak force; PP = peak power.
†Correlations significant at $p \leq 0.01$.

Table 6. Correlations between relative isometric force-time variables.*

Variable	Peak force ($N \cdot kg^{-1}$)	Max RFD ($N \cdot kg^{-1} \cdot s^{-1}$)	IMP100 ($N \cdot kg \cdot s$)	IMP200 ($N \cdot kg \cdot s$)	IMP300 ($N \cdot kg \cdot s$)	Total IMP ($N \cdot kg \cdot s$)
IPF ($N \cdot kg^{-1}$)	1.00	0.70†	0.29	0.30	0.28	0.43†
mRFD ($N \cdot kg^{-1} \cdot s^{-1}$)	0.70†	1.00	0.26	0.32	0.32	0.16
I100 ($N \cdot kg \cdot s$)	0.29	0.26	1.00	0.98‡	0.98‡	−0.03
I200 ($N \cdot kg \cdot s$)	0.30	0.32	0.98‡	1.00	0.99‡	0.01
I300 ($N \cdot kg \cdot s$)	0.28	0.32	0.98‡	0.99‡	1.00	−0.04
Total impulse ($N \cdot kg \cdot s$)	0.43†	0.16	−0.03	0.01	−0.04	1.00

*IMP = impulse; IPF = isometric peak force; mRFD = maximum rate of force development; I100 = impulse 100 ms; I200 = impulse 200 ms; I300 = impulse 300 ms.
†Correlations significant at $p \leq 0.05$.
‡Correlations significant at $p \leq 0.01$.

statistic and Q-Q plot analysis. Relationships between variables (IMTP and VJ performance, both absolute and relative) were determined using Pearson's product-moment correlation using SPSS software (version 17.0; SPSS, Inc.). Correlations were evaluated as follows: small (0.1–0.29), moderate (0.30–0.49), large (0.50–0.69), very large (0.70–0.89), nearly perfect (0.90–0.99), and perfect (1.0) (17). Additional analysis included comparisons of the strongest to the weakest athletes with respect to IMTP PF only. This additional analysis was performed to assist in confirming the primary findings of the study. Based on relative IPF (IPF divided by body mass), athletes were grouped into the strongest ($n = 11$) and weakest ($n = 11$). Two-tailed independent samples t-tests were used to assess differences between mean values of the stronger and weaker groups. Effect sizes were also calculated according to the formula Cohen's $d = \mathrm{M} - \mathrm{M2}/\sigma$ pooled, where σ pooled $= \sqrt{([\sigma 1^2 + \sigma 2^2/2])}$ (8). Effect sizes were modified as trivial (<0.19), small (0.20–0.59), moderate

Table 7. Comparison between stronger and weaker athletes in relative IMTP, CMJ, and SJ force-time and velocity-time variables.*†

	Strong ($n = 11$)	Weak ($n = 11$)	p	Effect size
Body mass (kg)	80.13 ± 8.28	75.98 ± 12.88	0.38	0.38
IMTP				
IPF ($N \cdot kg^{-1}$)	38.72 ± 2.08	30.40 ± 4.01	0.01	2.60
mRFD ($N \cdot kg^{-1} \cdot s^{-1}$)	172.59 ± 37.64	103.12 ± 35.95	0.01	1.89
I100 ($N \cdot kg \cdot s$)	1.03 ± 0.08	1.00 ± 0.03	0.22	0.50
I200 ($N \cdot kg \cdot s$)	2.05 ± 0.17	1.98 ± 0.05	0.19	0.56
I300 ($N \cdot kg \cdot s$)	3.09 ± 0.28	2.97 ± 0.08	0.20	0.58
Total IMP ($N \cdot kg \cdot s$)	140.38 ± 26.73	125.52 ± 20.05	0.16	0.63
CMJ				
PV ($m \cdot s^{-1}$)	2.99 ± 0.36	3.16 ± 0.22	0.20	−0.57
PF ($N \cdot kg^{-1}$)	26.95 ± 4.87	26.84 ± 5.48	0.96	0.02
PP ($W \cdot kg^{-1}$)	59.89 ± 10.59	65.15 ± 14.80	0.35	−0.41
Jump height (m)	0.33 ± 0.05	0.36 ± 0.05	0.19	−0.60
SJ				
PV ($m \cdot s^{-1}$)	2.68 ± 0.27	2.72 ± 0.18	0.64	−0.18
PF ($N \cdot kg^{-1}$)	27.12 ± 4.79	25.31 ± 4.79	0.39	0.38
PP ($W \cdot kg^{-1}$)	55.86 ± 7.51	54.88 ± 8.99	0.78	0.12
Jump height (m)	0.29 ± 0.06	0.33 ± 0.05	0.14	−0.72

*IMTP = isometric midthigh pull; CMJ = countermovement jump; SJ = squat jump; IPF = isometric peak force; mRFD = maximum rate of force development; IMP = impulse; I100 = impulse 100 ms; I200 = impulse 200 ms; I300 = impulse 300 ms; PV = peak velocity; PF = peak force; PP = peak power.
†Values are expressed as mean ± SD.

(0.60–1.19), large (1.20–1.99), and very large (2.0–4.0) (17). The criterion for statistical significance of the correlation was set at $p \leq 0.05$.

Results

The mean and *SD* values for strength and power performance variables of the IMTP, CMJ, and SJ in absolute and relative terms can be found in Table 1. The ICCs, %CV, TE, and change in the mean (%) for each IMTP and VJ variable are presented in Table 2.

Isometric Strength and Vertical Jump Characteristics

Pearson's correlation coefficients between IMTP and CMJ variables are presented in Table 2. When considering absolute IMTP performances, which did not account for body mass, and its correlation to CMJ performance, significant correlations existed. Isometric midthigh pull I100, I200, I300, and total IMP showed moderate to large significant correlations ($p \leq 0.05$) with CMJ PF. Isometric midthigh pull I100, I200, I300, and total IMP showed moderate to large significant correlations ($p \leq 0.05$) with CMJ PP. Our data show that IPF was significantly correlated with CMJ PF, but analysis revealed no significant correlations with CMJ PP. Results demonstrated that IPF, mRFD, I100, I200, I300, and total IMP were not significantly correlated with CMJ height. Furthermore, analysis revealed that there were no significant correlations between IPF, mRFD, I100, I200, I300, total IMP, and CMJ PV.

Pearson's correlation coefficients between IMTP and SJ variables are presented in Table 3. When considering absolute IMTP performances, which did not account for body mass, and its correlation to SJ performance, significant correlations existed. Isometric midthigh pull I100, I200, I300, and total IMP showed moderate to large significant correlations ($p \leq 0.05$) with SJ PF. Isometric midthigh pull I100, I200, and I300 showed moderate to large significant correlations ($p \leq 0.05$) with SJ PP. Our data show that IPF was significantly correlated with SJ PP, but analysis revealed no significant correlations with SJ PF. Results demonstrated that IPF, mRFD, I100, I200, I300, and total IMP were not significantly correlated with SJ height. Furthermore, analysis revealed that there were no significant correlations between IPF, mRFD, I100, I200, I300, total IMP, and SJ PV.

Strong Athlete Group and Weak Athlete Group Comparisons

Differences between relatively strong athlete and weak athlete group mean values are presented in Table 4. The strong group had a greater body mass than the weak group (strong = 80.13 ± 8.28 kg; weak = 75.95 ± 12.88 kg). Statistically significant differences ($p \leq 0.01$) were found between groups on relative IPF and relative IMTP RFD, respectively. The strong group had a statistically significant greater relative IPF and relative mRFD than the weaker group. The strong group had greater relative I100, I200, I300, and relative total IMP, respectively, than the weak group; however, it was not statistically significant.

There was no statistical difference in relative CMJ PF, relative SJ PF, and relative SJ PP, between stronger and weaker athletes.

There was no statistical difference in CMJ PV, SJ PV, relative CMJ PP, CMJ height, and SJ height between stronger and weaker athletes (Tables 5–7).

Discussion

The aims of this study were to determine the relationships between maximal isometric strength variables and measurements of VJ performance and establish whether athletes who have high performance in isometric strength testing would have high performance in VJ performance measures. Our results suggest that absolute measures of IMTP strength, specifically IMP generated in ≤300 milliseconds, best correlate with PF and PP measures of VJ performance. In contrast to previous research (20,32), we have found that athletes who have significantly greater relative isometric strength levels jump the same height as those with lower relative isometric strength values.

Absolute IMTP performance measures do not significantly correlate with performance variables in the VJ such as PV and jump height; however, they do correlate with VJ PF and PP. Additionally, it seems that when comparing isometric tests (IMTP) to dynamic performance (VJ), underlying neural and mechanical mechanisms may cause correlations to be weaker than previously observed when comparing dynamic tests (1RM) to VJ performance (18,24,26).

A comparison of absolute IMTP strength measurements to VJ PV and jump height did not reveal any significant correlations. The findings in this study are in agreement with previous research that did not find any significant correlations between absolute IMTP strength and VJ height (14,15,26) but opposite to studies that found significant correlations between IMTP strength and VJ height (23–25). One possible reason is that in this experiment, jump height was determined from flight time, which may be limited by body configuration at takeoff and on landing (21). Haff et al. (14) also observed no significant correlation between IPF and VJ height when determined by flight time. In contrast, studies showing significant correlation between IPF and VJ height determine height jumped through jump and reach apparatus. Although highly practical instruments, research has shown jump and reach devices to be less valid measures of VJ height, compared with force plate (6). In addition, the use of an overhead goal has shown to produce significantly greater jump heights when compared with no overhead goal in collegiate athletes (11). Furthermore, observations should determine VJ height through takeoff velocity, given IMP has shown to be a strong predictor in VJ (22).

Additionally, our data show findings consistent with previous research that found absolute IPF significantly correlated with VJ PF and PP (14,15,19,26,35). Absolute IPF and PP values correspond to CMJ PF and PP because larger athletes have higher PF and PP values when performing VJ, whereas relative IPF is more likely to correlate with VJ PV and jump height because relative values determine the rate of acceleration, and thus velocity at takeoff during VJ. Previous research has demonstrated no significant correlations between IMTP RFD and VJ performance (15). Our findings are in agreement with previous studies that absolute IMTP mRFD observed no significant correlations with VJ performance measures (15,25,31,32), but in contrast to Haff et al. (14) who found significant correlations with VJ PP, Nuzzo et al. (26) who observed significant correlations with CMJ PP, and Kraska et al. (20) who observed significant correlations with CMJ and SJ height. Possible reasons for different findings may be because of how RFD was analyzed, with Haff et al and Kraska et al using sampling windows of 2 and 10 milliseconds, respectively, whereas this study divided force readings by 0.0017 seconds. Our findings show mRFD to observe a very high %CV (15.1); therefore, future research may be warranted in determining reliability for IMTP RFD measures using a variety of sampling windows (e.g., 2, 5, 10, 20 milliseconds) and time windows (e.g., 0–50, 0–100, 0–150, 0–200 milliseconds).

Absolute IMTP measures of IMP demonstrated the most consistent significant correlations with VJ PF and VJ PP. No studies have previously investigated IMP achieved during the IMTP as a measure of performance; however, other studies have analyzed IMTP forces at 50, 90, 100, and 250 milliseconds (20,35). Our findings demonstrate that absolute IMTP I100, I200, I300, and total IMP showed significant correlations with VJ PF and PP. Thus, maximizing IMP during explosive actions in training could prove to be highly desirable. This finding is consistent with previous research, which found significant correlations between absolute IMTP force at 100 milliseconds and CMJ power (35). Impulse is the integration of force and time (IMP = force $\times$ time), and thus, IMP determines the velocity of the object to which the IMP is applied, with research showing strong correlations between net vertical IMP and PV, and CMJ height (22). Additionally, previous data have shown force at 50, 90, and 250 milliseconds to significantly correlate with CMJ and SJ height (20). However, we found that relative IMTP IMP measurements did not reveal any significant correlations with VJ performance measures, possibly because of differences in scaling methods. Data in this study were normalized using ratio scaling, whereas Kraska et al. (20) and Stone et al. (32) use allometric scaling to normalize IPF. Research has shown allometric scaling may be able to normalize strength data between smaller and larger athletes; however, ratio scaling may provide more accurate measures of correlations between performance variables.

In addition, possible explanations for lack of statistical difference in VJ performance variables in this study are perhaps the difference in biomechanical characteristics of the IMTP and VJ. The IMTP involves an active isometric muscle contraction, the SJ an active concentric muscle action, and the CMJ an active eccentric muscle contraction, followed by a temporary isometric, and final active concentric muscle contraction. As maximal muscular power is determined by force and velocity, it seems that these variables are more complexly related during dynamic tasks (VJ), compared with an IMTP where no velocity variable exists and maximum force is the key attribute to performance. Vertical jump performance, CMJ in particular, requires efficient use of the SSC through increased eccentric force and velocity, resulting in and increased ability to translate momentum into concentric force (10).

This study observed no significant differences between strong and weak groups in any IMTP IMP measurement. In contrast to our findings, Kraska et al. (20) found significant differences between strong and weak groups in allometrically scaled force at 50, 90, and 250 milliseconds. In this investigation, stronger athletes produced greater CMJ PF but lower peak velocities, PP, and jump height than weaker athletes. When discussing SJ performance, stronger athletes produced greater PF and PP but lower peak velocities and jump height than weaker athletes. Surprisingly, there was no statistical difference in jump heights in both CMJ and SJ when comparing stronger and weaker athletes. This finding is in agreement with previous research, which found no statistical difference in CMJ and SJ height in stronger vs. weaker athletes based on allometrically scaled IPF in both CMJ and SJ (20). Additionally, Stone et al. (32) found significant differences in absolute and allometrically scaled IPF, CMJ PP, and allometrically scaled CMJ PP between stronger and weaker cyclists based on absolute IPF. These findings could be limited by the homogeneity of the group in this study. Similar to Kraska et al. (20), athletes were selected from several team and individual sports; however, it could be speculated that Kraska et al athletes were of a higher training status than athletes in this study based on the relative IMTP force-time measures. Therefore, further observations are warranted to establish normative values for relative IMTP force-time variables in a range of athletic populations to benchmark standards for use in athlete monitoring and strength assessment.

Although significant differences were observed between relative isometric strength measurements, it is unknown whether these findings would transfer to relative dynamic strength (e.g., 1RM back squat) in the athletes used within this study. Previous research has found IPF to show a strong correlation to 1RM back squat ($r = 0.96$) and 1RM power clean ($r = 0.97$) in collegiate wrestlers and recreationally trained males. (23,25). Thus indicating, although isometric and dynamic strength assessments differ in biomechanical and neuromuscular characteristics, these findings may imply that the IMTP is a valid and reliable test of maximal dynamic strength (e.g., 1RM back squat, 1RM power clean). However, further research may be warranted to investigate future profiling of isometric and dynamic maximal strength performance and their relationship with lower-body force, velocity, and power during dynamic tasks (VJ height, sprinting, COD) in collegiate athletes.

Practical Applications

Strength and conditioning coaches and sports scientists should consider biomechanical characteristics (force, RFD, power, and IMP) when constructing testing protocols, taking into consideration important concepts such as validity and reliability of the selected tests. These factors will help guide assessment, monitoring, and training of athletes in an integrative fashion to develop key physical attributes to optimize sports performance. Furthermore, the development of these characteristics (force, RFD, power, and IMP) should be developed in a periodized manner to ensure appropriate development of each component dependent on the athletes' specific needs, as identified through appropriate assessment.

References

1. Appleby, B, Newton, RU, and Cormie, P. Changes in strength over a 2-year period in professional rugby union players. *J Strength Cond Res* 26: 2538–2546, 2012.
2. Baker, D, Wilson, G, and Carlyon, B. Generality versus specificity: A comparison of dynamic and isometric measures of strength and speed-strength. *Eur J Appl Physiol Occup Physiol* 68: 350–355, 1994.
3. Beckham, G, Mizuguchi, S, Carter, C, Sato, K, Ramsey, M, Lamont, H, Hornsby, G, Haff, G, and Stone, M. Relationships of isometric mid-thigh pull variables to weightlifting performance. *Int J Sports Med* 53: 573–581, 2013.
4. Behm, DG, Wahl, MJ, Button, DC, Power, KE, and Anderson, KG. Relationship between hockey skating speed and selected performance measures. *J Strength Cond Res* 19: 326–331, 2005.
5. Bencke, J, Damsgaard, R, Saekmose, A, Jorgensen, P, Jorgensen, K, and Klausen, K. Anaerobic power and muscle strength characteristics of 11 years old elite and non-elite boys and girls from gymnastics, team handball, tennis and swimming. *Scand J Med Sci Sports* 12: 171–178, 2002.
6. Buckthorpe, M, Morris, J, and Folland, JP. Validity of vertical jump measurement devices. *J Sports Sci* 30: 63–69, 2012.
7. Carlock, JM, Smith, SL, Hartman, MJ, Morris, RT, Ciroslan, DA, Pierce, KC, Newton, RU, Harman, EA, Sands, WA, and Stone, MH. The relationship between vertical jump power estimates and weightlifting ability: A field-test approach. *J Strength Cond Res* 18: 534–539, 2004.
8. Cohen, J. *Statistical Power Analysis for the Behavioral Sciencies.* Lawrence Erlbaum Associates, Incorporated, 1988.
9. Comfort, P and Pearson, SJ. Scaling–Which methods best predict performance? *J Strength Cond Res* 28: 1565–1572, 2014.
10. Cormie, P, McGuigan, MR, and Newton, RU. Developing maximal neuromuscular power. *Sports Med* 41: 17–38, 2011.
11. Ford, KR, Myer, GD, Smith, RL, Byrnes, RN, Dopirak, SE, and Hewett, TE. Use of an overhead goal alters vertical jump performance and biomechanics. *J Strength Cond Res* 19: 394–399, 2005.
12. Fry, AC and Kraemer, WJ. Physical performance characteristics of american collegiate football players. *J Strength Cond Res* 5: 126–138, 1991.
13. Gabbett, TJ, Jenkins, DG, and Abernethy, B. Relative importance of physiological, anthropometric, and skill qualities to team selection in professional rugby league. *J Sports Sci* 29: 1453–1461, 2011.
14. Haff, GG, Carlock, JM, Hartman, MJ, Kilgore, JL, Kawamori, N, Jackson, JR, Morris, RT, Sands, WA, and Stone, MH. Force-time curve characteristics of dynamic and isometric muscle actions of elite women olympic weightlifters. *J Strength Cond Res* 19: 741–748, 2005.
15. Haff, GG, Stone, M, O'Bryant, HS, Harman, E, Dinan, C, Johnson, R, and Han, K-H. Force-time dependent characteristics of dynamic and isometric muscle actions. *J Strength Cond Res* 11: 269–272, 1997.
16. Hopkins, WG. Measures of reliability in sports medicine and science. *Sports Med* 30: 1–15, 2000.
17. Hopkins, WG. A scale of magnitudes for effect statistics. 2002. Available at: http://sportsciorg/resource/stats/effectmaghtml. Accessed October 20, 2013.
18. Hori, N, Newton, RU, Andrews, WA, Kawamori, N, McGuigan, MR, and Nosaka, K. Does performance of hang power clean differentiate performance of jumping, sprinting, and changing of direction? *J Strength Cond Res* 22: 412–418, 2008.
19. Kawamori, N, Rossi, SJ, Justice, BD, Haff, EE, Pistilli, EE, O'Bryant, HS, Stone, MH, and Haff, GG. Peak force and rate of force development during isometric and dynamic mid-thigh clean pulls performed at various Intensities. *J Strength Cond Res* 20: 483–491, 2006.
20. Kraska, JM, Ramsey, MW, Haff, GG, Fethke, N, Sands, WA, Stone, ME, and Stone, MH. Relationship between strength characteristics and unweighted and weighted vertical jump height. *Int J Sports Physiol Perform* 4: 461–473, 2009.
21. Linthorne, NP. Analysis of standing vertical jumps using a force platform. *Am J Phys* 69: 1198–1204, 2001.
22. McBride, JM, Kirby, TJ, Haines, TL, and Skinner, J. Relationship between relative net vertical impulse and jump height in jump squats performed to various squat depths and with various loads. *Int J Sports Physiol Perform* 5: 484–496, 2010.
23. McGuigan, MR, Newton, MJ, Winchester, JB, and Nelson, AG. Relationship between isometric and dynamic strength in recreationally trained men. *J Strength Cond Res* 24: 2570–2573, 2010.
24. McGuigan, MR and Winchester, JB. The relationship between isometric and dynamic strength in college football players. *J Sports Sci Med* 7: 101–105, 2008.
25. McGuigan, MR, Winchester, JB, and Erickson, T. The importance of isometric maximum strength in college wrestlers. *J Sports Sci Med* 5: 108–113, 2006.
26. Nuzzo, JL, McBride, JM, Cormie, P, and McCaulley, GO. Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. *J Strength Cond Res* 22: 699–707, 2008.
27. Ravier, G, Grappe, F, and Rouillon, JD. Application of force-velocity cycle ergometer test and vertical jump tests in the functional assessment of karate competitor. *J Sports Med Phys Fitness* 44: 349–355, 2004.
28. Sheppard, JM, Gabbett, TJ, and Stanganelli, LC. An analysis of playing positions in elite men's volleyball: Considerations for competition demands and physiologic characteristics. *J Strength Cond Res* 23: 1858–1866, 2009.
29. Sheppard, JM, Nolan, E, and Newton, RU. Changes in strength and power qualities over two years in volleyball players transitioning from junior to senior national team. *J Strength Cond Res* 26: 152–157, 2012.
30. Stone, MH, O'Bryant, HS, McCoy, L, Coglianese, R, Lehmkuhl, M, and Schilling, B. Power and maximum strength relationships during performance of dynamic and static weighted jumps. *J Strength Cond Res* 17: 140–147, 2003.
31. Stone, MH, Sanborn, K, O'Bryant, HS, Hartman, M, Stone, ME, Proulx, C, Ward, B, and Hruby, J. Maximum strength-power-performance relationships in collegiate throwers. *J Strength Cond Res* 17: 739–745, 2003.
32. Stone, MH, Sands, WA, Carlock, J, Callan, SAM, Dickie, DES, Daigle, K, Cotton, J, Smith, SL, and Hartman, M. The importance of isometric maximum strength and peak rate-of-force development in sprint cycling. *J Strength Cond Res* 18: 878–884, 2004.
33. Stone, MH, Sands, WA, Pierce, KC, Carlock, J, Cardinale, M, and Newton, RU. Relationship of maximum strength to weightlifting performance. *Med Sci Sports Exerc* 37: 1037–1043, 2005.

34. Vizcaya, FJ, Viana, O, del Olmo, MF, and Acero, RM. Could the deep squat jump predict weightlifting performance?. *J Strength Cond Res* 23: 729–734, 2009.

35. West, DJ, Owen, NJ, Jones, MR, Bracken, RM, Cook, CJ, Cunningham, DJ, Shearer, DA, Finn, CV, Newton, RU, and Crewther, BT. Relationships between force–time characteristics of the isometric midthigh pull and dynamic performance in professional rugby league players. *J Strength Cond Res* 25: 3070–3075, 2011.

36. Weyand, PG, Lin, JE, and Bundle, MW. Sprint performance-duration relationships are set by the fractional duration of external force application. *Am J Physiol Regul Integr Comp Physiol* 290: R758–R765, 2006.

37. Weyand, PG, Sternlight, DB, Bellizzi, MJ, and Wright, S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol* 89: 1991–1999, 2000.

38. Wilson, GJ, Lyttle, AD, Ostrowski, KJ, and Murphy, AJ. Assessing dynamic performance: A comparison of rate of force development tests. *J Strength Cond Res* 9: 176–181, 1995.

39. Wisloff, U, Castagna, C, Helgerud, J, Jones, R, and Hoff, J. Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *Br J Sports Med* 38: 285–288, 2004.

40. Young, W, Wilson, G, and Byrne, C. Relationship between strength qualities and performance in standing and run-up vertical jumps. *J Sports Med Phys Fitness* 39: 285–293, 1999.

41. Young, WB and Bilby, GE. The effect of voluntary effort to influence speed of contraction on strength, muscular power, and hypertrophy development. *J Strength Cond Res* 7: 172–178, 1993.

42. Young, WB, James, R, and Montgomery, I. Is muscle power related to running speed with changes of direction? *J Sports Med Phys Fitness* 42: 282–288, 2002.