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ORIGINAL ARTICLE

Relationships Between Vertical Jump Metrics and Sprint Performance, and Qualities that Distinguish Between Faster and Slower Sprinters

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Abstract
Purpose This study aimed to investigate the relationships between vertical jump metrics and phases during a 60 m sprint. The variances in strength qualities between sprinters of different ability levels were also compared.
Methods Eighteen young male elite sprinters (age: 18.1 ± 1.3 years; stature: 1.72 ± 0.07 m; body mass: 66.3 ± 6.2 kg) were assessed for squat (SJ), countermovement (CMJ), drop (DJ), and standing long jumps, a maximal load back-squat, and a 60-m sprint from a block-start. The relationships between sprint performances with all variables were analysed using correlation and multiple regression while discriminative parameters between fast (100 m time: ~ 10.50 s) and slow (~ 11.00 s) sprint groups were assessed using independent *t*-tests.
Results Higher associations existed between vertical jumps and longer sprint distances, especially between SJ height and relative peak power with 10 m ($r = -0.47$ and -0.47, respectively), 30 m (-0.71 and -0.74), 60 m (-0.76 and -0.81), 10–30 m (-0.80 and -0.86), and 30–60 m (-0.78 and -0.84) sprint distances. Concurrently, variables such as relative maximal-strength, relative SJ parameters (height, peak force, and peak power), relative CMJ peak power, and reactive strength index (DJ from 35 cm height) had significant discriminative ability and correlations ($P < 0.05$) with sprint distances involving maximal velocity and flying-start. Additionally, a combination of SJ height and relative maximal-strength during back-squat accounted for 75% of the variance in 60 m sprint times.
Conclusions Relative measures of multiple strength metrics may provide better insight regarding factors that enhance sprint performance. Adequate maximal-strength, high explosive power, and reactive strength seem necessary to improve sprint performance in young male elite sprinters.

Keywords Acceleration · Mechanical power · Maximum strength · Neuromuscular abilities · Reactive strength · Track and field

Introduction

Sprint performance relies on different physiological factors throughout sprint phases [8]. Exerting higher levels of horizontal force seems to result in greater propulsion, which in turn enhances acceleration [14]. As sprint distance increases, ground contact time (GCT) tends to decrease while time spent to generate force is at its lowest. Thus, the ability to produce reactive forces and fast stretch–shortening cycles become more crucial during the maximal velocity phase [12, 15, 18]. Therefore, to reach maximal velocity, sprinters need to accelerate by increasing lower-limb power to enhance sprinting parameters including GCT, flight time, and stride frequency [15].

High levels of force and speed are required to generate high levels of power needed for sprinting [11, 28, 30]. As such, mechanical output (e.g., power) of the lower-limb muscles must be enhanced [16], and developed appropriately using muscle actions that maximise force and speed [30]. For sprinting, such qualities are usually developed using exercises that involve a vigorous extension of the lower limbs, simulating the proximal-to-distal hip, knee,

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ankle sequencing during sprinting that allow maintenance of sprint velocity effectively [17]. Traditionally, these movements are trained by using weightlifting [31], and plyometric or explosive jumping exercises such as forward, squat and drop jumping. Perhaps, due to simplicity and practicality, these vertical and horizontal jump exercises have also been used for assessing and predicting relationships with sprint performance [8, 12, 15, 23, 29, 33, 37].

Numerous studies have identified parameters of jump metrics most strongly associated with sprint performance. Strong correlations between countermovement jump (CMJ) and squat jump (SJ) heights with 60 and 100-m sprint performance were similarly found in young beginner male sprinters [29]. Another study [15] reported moderate relationships among CMJ, SJ, and drop jump (DJ) heights with 100-m sprint times, but strong relationships between the same jumps with maximal velocity. More recently, large correlation indices were found between jump heights and distances reached during vertical and horizontal jumps, as well as between loaded vertical jumps and sprint speeds in male and female elite sprinters [19]. Another sample of male elite sprinters (100 m time: ~ 10.28 s) recorded very large correlation indices between 100-m sprint times and CMJ ($r = -0.85$) and SJ ($r = -0.82$) heights, and jump distance ($r = -0.81$) during standing long jumps (SLJ) [20]. Studies involving other sports, such as female rugby players (example of sports) found significant relationships between CMJ ($r = -0.56$ to -0.68) as well as DJ heights from various heights ($r = -0.56$ to -0.86) with 10 m sprint times, 10–30 m and 30–60 m split times [2].

It can be concluded that numerous studies have examined the relationships between explosive tasks and sprint performance, but few if any have observed the relationship between jump kinetics such as force and mechanical power during loaded SJ and CMJ, or DJ parameters with sprint times for different distances or sprint phases for young male elite sprinters. Furthermore, there is also a gap in literature examining if the above mentioned variables could be affected by sprint ability which differs between fast sprinters and those who are slower. Therefore, this study assessed the relationships between ballistic strength metrics during loaded and unloaded vertical jumps, and sprint performance, and compared the results between fast and slower young male sprinters. Based on current published literature, it was hypothesised that strong relationships would exist between jump metrics and sprint performance due to the ability of elite sprinters to perform better in explosive tasks, and that faster sprinters would exhibit superior strength and power compared with slower sprinters.

Methods

Experimental Design

A cross-sectional design was used to examine the relationships between ballistic strength metrics of loaded and unloaded vertical jumps and sprint performance in young male sprinters. Sprint performance over 60 m was tested to allow a regression analysis of different sprint phases with vertical jump parameters. Additionally, maximal strength (one-repetition maximum [1RM] back-squat), and SLJ tests were performed. The sample was also divided based on recent 100 m times to form a fast-sprint (FSG) and a slow-sprint group (SSG) to determine if any dependent variable differentiated according to sprint ability as this allowed a better understanding of discriminative qualities, as well help determine priorities for strength and power development and monitoring.

Participants

Eighteen young male participants (aged 17–19 years, Table 1) comprising sprinters who have competed in age-group national, regional and world championships, participated in the study. The recent 100-m personal bests for these sprinters (taken within 12 months prior to or after the assessment) ranged from 10.18 to 11.14 s and they were divided to FSG ($n = 9$) and SSG ($n = 9$) groups ($P = 0.001$,

Table 1 Comparisons of age, anthropometric measures, and best 100-m times between SSG and FSG (mean ± standard deviation)

	All ($n = 18$)	SSG ($n = 9$)	FSG ($n = 9$)	*P* value	ES 90% (CI), descriptor
Age (y)	18.1 ± 1.3	17.6 ± 1.42	18.6 ± 1.01	0.075	0.74 (0.47, 1.00), M
Stature (m)	1.72 ± 0.07	1.74 ± 0.06	1.70 ± 0.08	0.241	− 0.53 (− 0.79, − 0.26), M
Body mass (kg)	66.3 ± 6.2	67.9 ± 6.4	64.7 ± 7.7	0.281	− 0.46 (− 0.72, − 0.20), S
Body mass index (kg m^2)	22.3 ± 1.5	22.4 ± 1.5	22.3 ± 1.7	0.271	0.19 (− 0.07, 0.45), T
100-m personal best (s)	10.75 ± 0.29	**11.00 ± 0.08**	**10.50 ± 0.18**	**0.001***	− 2.08 (− 2.40, − 1.76), L

SSG slow-sprint group, *FSG* fast-sprint group, *ES* effect size, *CI* confidence interval, *T* trivial, *S* small, *M* moderate, *L* large

*Significant at $P < 0.05$ (bolded)

Table 1). The mean 100-m time (10.50 ± 0.18 s) of the FSG was within the qualifying standard (10.58 s) of the IAAF (now World Athletics) World U20 Championships, confirming that these sprinters were high-caliber U20 sprinters (www.worldathletics.org). Written informed consent were obtained from participants and their guardians after they were briefed on the experimental risks and benefits. The study was approved by the Institutional Ethics Committee and the investigation was conducted in accordance with the ethical standards of the Declaration of Helsinki.

Procedures

Assessments were conducted during unloading week at the end of the preparation phase. All tests were completed within a 3-day period. Vertical jumps were performed using a force plate (Fitness Technology, Adelaide, Australia), which sampled at a rate of 600 Hz. During the first experimental session (day 1 am), participants performed unloaded and loaded SJ and CMJ tests. An absolute load of 20 kg was used for both SJ (SJ20) and CMJ (CMJ20). In the second session (day 1 pm), DJ from 35 cm (DJ35) and 50 cm (DJ50) heights, and SLJ were performed. In the third session (day 2 pm), a 60-m sprint was performed. The maximal strength test was performed during the fourth session (day 3 p.m.). Participants have previously performed all test procedures, and wore appropriate clothing and shoes (for warm-up and jumps) or track spikes (for sprint trials) during testing. They had a passive rest day before commencing the experiment, which coincided with their normal scheduled training time. A standardised 40–45 min warm up that included rhythmic low-intensity runs, dynamic stretching, sprint drills, submaximal sprinting, and block start practice was conducted before the sprint tests. A general warm up for the jump and strength tests was performed for about 10–15 min and consisted of dynamic stretching exercises that included fast movement drills, submaximal jumps and lifts. A few sets of light-load squats were performed before the 1RM back-squat test.

Jumping

Vertical Jumps

All jumps were executed with hands akimbo throughout the full range of the movements. For SJs, participants were asked to maintain a static position at ~ 85° of knee flexion for 2 s before jumping explosively upwards, without a pre-stretch movement. During CMJs, participants executed a rapid downward movement to semi-squat position (~ 85°) followed by a vigorous extension of the lower limb joints. In both SJs and CMJs, athletes were verbally asked to “jump as high as possible,” before every trial. For DJs, participants were asked to drop from a given height, and immediately jump upwards vigorously, with a strict vertical displacement, after minimal ground contact to achieve maximal rebound height. A standardised instruction was given before every DJ trial, which was “fast contact, and jump higher.” SJs, CMJs and DJs required each participant to jump and land approximately on the same positions of the force plate. For each test, three maximal effort repetitions with approximately 30–60 s rest between trials were performed for all jumps [15, 33, 34].

During SJ and CMJ, peak force (F_{PEAK}), peak power (P_{PEAK}), and jump height (JH) were produced instantaneously via custom-designed software (Ballistic Measurement System, Innervations, Australia), and the trial with the highest score was used for analysis. The relative values for F_{PEAK} and P_{PEAK} were obtained by dividing with the body mass. The RSI was determined during DJ from the ratio between JH and ground contact time (GCT), by dividing the JH by GCT. Flight time (FT), determined from the instant take-off was performed until subsequent ground contact upon landing, was used to determine JH, based on the equation of uniform acceleration which states: $JH = 9.81 \times (FT \times FT)/8$ [3, 34].

Horizontal Jumps

The SLJ was performed from the take-off board on to a long jump landing pit from a standing position, with feet shoulder-width apart. Participants were allowed to use pre-stretch to a self-selected depth, and arm-swing during the jump for maximal forward drive. The distance jumped was recorded to the nearest 1 cm with a tape measure. Three trials were performed with approximately 5 min rest between trials. The best trial was used for analysis [15].

Sprint Performance

The 60-m sprint test was performed on an outdoor synthetic track. The sprinters performed two all-out 60-m sprint with a minimum of 15 min rest given between trials, with the faster time used for analysis. Sprint times for 10, 30 and 60 m were measured, as well as 20-m (between 10–30 m) and 30-m (between 30–60 m) sprints from flying starts, were measured using four pairs of dual-beam timing gates (Swift Performance Technology, Brisbane Australia). Participants were required to use starting blocks fixed 50 cm behind the first pair of timing gates as so as to trigger the timing device with actual sprint movements [33].

Maximal Strength

Participants have strength training experience and performed back-squat exercise to predict their 1RM score using the

Epley equation [9]. After a 10–15 min general warm-up, participants performed 10 repetitions with an unloaded barbell, followed by 8 repetitions at 50%, then 5 repetitions at 70%, and 3 repetitions at 80% of estimated 1RM. The load intensity was increased or decreased by 5–20 kg in the subsequent trials (i.e., up to four attempts) to achieve 3RM. During all trials, participants were required to lower the bar until a knee angle of ~ 85° was formed, and this was visually confirmed by the assessor. A rest period of 3–5 min was given between trials.

Statistical Analysis

Descriptive statistics were presented as mean ± standard deviation (SD). The reliability of testing was assessed using intraclass correlation coefficients (ICC) and the coefficient of variation (CV). ICC criteria was accepted to be excellent for values > 0.75, moderate for values 0.40–0.75, and low for values < 0.40 [10]. A visual examination of histograms and the Shapiro-Wilks test was used to confirm normal distribution of data. Pearson product-moment correlations or Spearman's correlation coefficient was used (where appropriate) to determine the strength of relationship, and interpreted qualitatively using a scale of magnitude: < 0.10 = trivial; 0.10–0.29 = small; 0.30–0.49 = moderate; 0.50–0.69 = large; 0.70–0.89 = very large; 0.90–0.99 = nearly perfect; and 1.00 = perfect [13]. Stepwise multiple regression analysis was utilised to determine the predictive ability for sprint performance, with the jump and strength variables as independent variables. Coefficients of determination ($R^2 \times 100$) was used throughout the manuscript. Independent *t*-tests were used to determine differences between SSG and FSG performances. Effect sizes (ES) were measured using Cohen's *d* to analyse between-group differences with confidence limits (CL), and were qualitatively interpreted using the following thresholds: < 0.20 = trivial, 0.20–0.49 = small, 0.50–0.79 = moderate, and ≥ 0.80 = large [5]. The significance level was set at $P < 0.05$. Analysis was performed using SPSS statistical software version 16.0 (SPSS, Inc., Chicago, IL, USA).

Results

Generally, the ICCs for all tests were excellent and greater than 0.82. The CV for all tests were between 1.0% to 5.3%.

The correlation between the 60 m sprint and best 100 m time was significant ($P = 0.001$) and nearly perfect ($r = 0.90$). Significant and very large correlations were found in various correlations between loaded and unloaded SJ and CMJ with different sprint distances, mostly reaching maximal velocities (Table 2).

Furthermore, significant correlation ($P < 0.05$) was detected between DJ35 GCT and 10–30 m ($r = 0.47$), and DJ35 RSI with 30 m ($r = -0.61$), 60 m ($r = -0.64$), 10–30 m ($r = -0.68$), and 30–60 m ($r = -0.66$) sprint distances (Fig. 1). Significant correlation ($P < 0.05$) was also detected for relative 1RM strength with 60 m ($r = -0.51$), 10–30 m ($r = -0.49$), and 30–60 m ($r = -0.53$) sprint distances (Fig. 2).

Meanwhile, a combination of multiple variables (e.g., 2 predictors) accounted for 75%–82% of the variance for 60 m, 30–60 m, and 10–30 m sprint distances (Table 3).

Finally, the sprint times for all distances distinguished between SSG and FSG groups ($P < 0.05$). Significant differences were also observed in several parameters during unloaded SJ and CMJ, and DJ35 between SSG and FSG (Table 4).

Discussion

The results suggest that the strength of relationships between sprint performances with other measured variables tended to be greater as sprint distances increased. Higher associations were found between vertical jumps and sprint distances greater than 10 m, especially for SJ height, relative F_{PEAK} and P_{PEAK} (Table 2). The same SJ parameters, and variables such as relative CMJ P_{PEAK}, DJ35 RSI, and relative strength (1RM squat/BM) had significant discriminative ability as well as correlations with the 60 m sprint, and the flying 10–30 m, and 30–60 m. Furthermore, the combination of SJ height and relative strength accounted for 75% of the variance in the 60 m sprint. The inclusion of SJ, CMJ and DJ parameters provided more information regarding factors influencing sprint performance that could also help coaches and sports scientists select key parameters to employ during testing and monitoring.

The use of relative jump parameters seemed better at predicting sprint performances than by utilising only absolute jump parameters. Such findings may be due to "physiomechanical similarities" [15] between vertical jump and sprinting (e.g., flexion/extension actions, and foot contact), which increased force production at ground contact (i.e., improves stride length) and rapid leg swings (i.e., increases stride frequency) at distances reaching maximum speed. The current results concur that it seems necessary to analyse relative jump parameters when examining a homogenous sample of track and field athletes [22]. In contrast, a study that analysed absolute scores during SJ and CMJ found them not highly related with sprint velocities ($r < 0.50$) [19].

Recently, a study examining high performing sprinters and jumpers found very large correlations between non-kinetic measures (i.e., JH) with sprint performance over 60 m [21]. This is consistent with the current, and another

Table 2 Relationships between sprint times and parameters collected during squat and countermovement jump in sprinters (*r* values)

	10 m	30 m	60 m	10-30 m	30-60 m
Squat jump					
F_{PEAK} (N)	0.08	0.00	− 0.16	− 0.06	− 0.26
P_{PEAK} (W)	0.20	− 0.31	− 0.24	− 0.30	− 0.44
JH (m)	**− 0.47***	**− 0.71****	**− 0.76****	**− 0.80****	**− 0.78****
F_{PEAK}/BM (N/kg)	− 0.44	**− 0.68****	**− 0.75****	**− 0.76****	**− 0.78****
P_{PEAK}/BM (W/kg)	**− 0.47***	**− 0.74****	**− 0.81****	**− 0.86****	**− 0.84****
Countermovement jump					
F_{PEAK} (N)	**0.52***	**0.49***	0.44	**0.47***	0.31
P_{PEAK} (W)	0.03	− 0.02	− 0.13	− 0.13	− 0.26
JH (m)	− 0.28	**− 0.54***	**− 0.55***	**− 0.76****	**− 0.62****
F_{PEAK}/BM (N/kg)	0.33	0.27	0.34	0.28	0.29
P_{PEAK}/BM (W/kg)	− 0.44	**− 0.60****	**− 0.67****	**− 0.74****	**− 0.73****
Loaded squat jump					
F_{PEAK} (N)	− 0.14	− 0.03	− 0.15	0.04	− 0.17
P_{PEAK} (W)	0.31	0.12	− 0.07	− 0.16	− 0.27
JH (m)	0.00	− 0.22	− 0.36	− 0.40	− 0.42
F_{PEAK}/BM (N/kg)	**− 0.51***	**− 0.49***	**− 0.54***	− 0.45	− 0.44
P_{PEAK}/BM (W/kg)	− 0.16	− 0.47	**− 0.57***	**− 0.77****	**− 0.67****
Loaded countermovement jump					
F_{PEAK} (N)	0.15	0.32	0.30	0.41	0.26
P_{PEAK} (W)	0.22	0.04	− 0.19	− 0.25	− 0.41
JH (m)	− 0.04	− 0.39	**− 0.52***	**− 0.66****	**− 0.63****
F_{PEAK}/BM (N/kg)	− 0.28	− 0.17	− 0.04	− 0.02	0.04
P_{PEAK}/BM (W/kg)	− 0.33	**− 0.60****	**− 0.63****	**− 0.83****	**− 0.67****

F force, *P* power, *JH* jump height, *BM* body mass

*Significant at $P<0.05$ (bolded)

**Significant at $P<0.01$ (bolded)

study that examined young male sprinters (aged ~ 18y) that reported significant and large correlations between JH during SJ and CMJ, and acceleration and maximal speed during a 100-m sprint [29]. It is important to note that JH was not always related to sprint performance [23]. To resolve this, the present study examined JH and also kinetic parameters related to the vertical jump such as F_{PEAK} and P_{PEAK}, which provided further insight into variables that improved sprint performance, as also noted previously [7, 8]. The present study also found that when SJ was performed with a 20-kg absolute load, relative jump parameters (F_{PEAK} and P_{PEAK}) related significantly with different phases of sprint performance (Table 2). Supporting the utility of absolute load is a study that found kinetic parameters (e.g., relative F_{PEAK}) during loaded SJ (i.e., 19 kg) to be very strongly correlated with a 2.5 m time (i.e., starting ability) from a block start [37]. More recently, high correlations were also found between an optimal load during SJ and sprint performance ($R^2=0.72$) [19].

Taken together, it may be reasonable to suggest that explosive performance under both concentric only (during SJ) and slow stretch–shortening cycle (during CMJ) are important during the acceleration (i.e., 0-to-top-speed), where a rapid increase in hip extension velocity occurs while exerting high ground reaction force [24], which help facilitate an effective transition from low to high velocities during sprinting [32].

Meanwhile, the findings of non-significant moderate to weak correlations between DJ parameters including the DJ35 RSI with 10 m sprint ($r=-0.36$) was not entirely unexpected. The weaker relationship between early acceleration and DJ parameters (i.e., RSI) may be ascribed to reduced mechanical specificity as DJ accentuates vertical force generation, while the early acceleration phase during sprinting stresses horizontal force production. Nevertheless, it seems that the above relationships in DJ and sprint performance are strengthened ($r>0.60$) when the sprint distance increases, as indicated by stronger associations found between DJ35 RSI and distances reaching maximal velocity (Fig. 1). This reinforces previous findings [29] that found stronger relationships between DJ height with 100-m sprint times ($r=0.69$) in male sprinters [15], and RSI during DJ with sprint performance over 30 m ($r=-0.79$) and 100 m ($r=-0.75$) in female high school sprinters [12]. The improved correlation

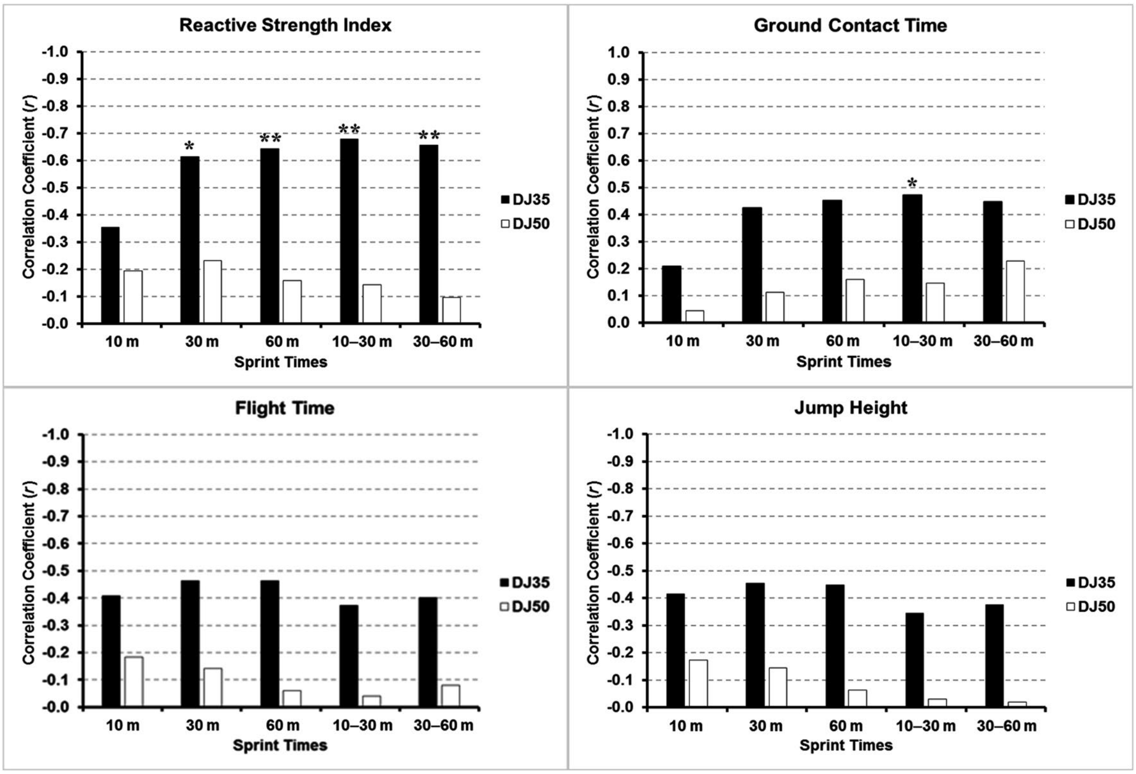

Fig. 1 Relationships between sprint times for the different distances with parameters collected during drop jump, from 35 cm (DJ35) and 50 cm (DJ50) drop heights. *Significant at $P < 0.05$, **Significant at $P < 0.01$

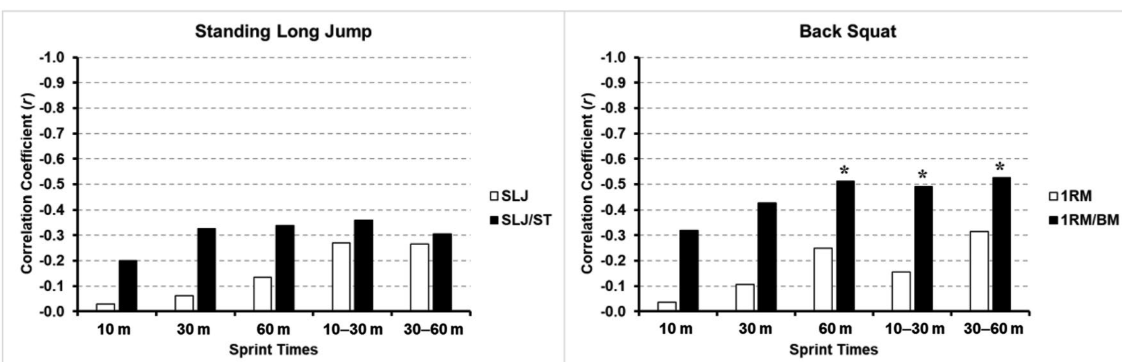

Fig. 2 Relationships between sprint times for the different distances with one-repetition maximum (1RM) during back-squat, squat/body mass (BM), standing long jump (SLJ), and SLJ/stature (ST). *Significant at $P < 0.05$

coefficients as sprint distances increased may have been influenced by the shorter contact time, and greater vertical force production during the maximal velocity phase [36]. Recent and contradictory results found non-significant relationships between RSI and sprint distances ranging from 10 to 60 m in a group of sprinters and jumpers [21]. However, the GCT values in this study mostly exceeded 250 ms, resulting in marked reductions in RSI values (i.e., < 1.20). High GCTs exceeding 250 ms would not be considered fast stretch–shortening cycles [28], while high-velocity sprinting relies heavily on reactive strength and fast or short stretch–shortening cycles [12, 15, 18, 33]. These findings have implications on sprint training regimens composed of vertical jumps.

Meanwhile, the present results are in dispute with the studies by Loturco et al. [19, 20] that found strong associations between SLJ and sprinting speed, including the actual 100 m sprint tested several weeks before competition.

Table 3 Best single-, and multiple-predictor regression models for sprint performance combining vertical jump metrics, 1RM strength, and standing long jump

	Best predictor	R^2	Adj R^2	SE	*P* value
10 m sprint					
Single predictor	SJ JH	0.22	0.18	0.053	0.048
30 m sprint					
Single predictor	SJ JH	0.54	0.51	0.063	< 0.001
60 m sprint					
Single predictor	SJ JH	0.65	0.63	0.094	< 0.001
2 predictors	SJ JH, 1RM squat/BM	0.75	0.72	0.082	< 0.001
10–30 m sprint					
Single predictor	SJ JH	0.73	0.71	0.024	< 0.001
2 predictors	SJ JH, CMJ20 P_{PEAK}	0.82	0.80	0.020	< 0.001
3 predictors	SJ JH, CMJ20 P_{PEAK}, DJ50 GCT	0.88	0.85	0.018	< 0.001
4 predictors	SJ JH, CMJ20 P_{PEAK}, DJ50 GCT, CMJ JH	0.92	0.89	0.015	< 0.001
30–60 m sprint					
Single predictor	SJ P_{PEAK}/BM	0.68	0.66	0.428	< 0.001
2 predictors	SJ P_{PEAK}/BM, DJ35 RSI	0.77	0.74	0.038	< 0.001
3 predictors	SJ P_{PEAK}/BM, DJ35 RSI, 1RM squat	0.86	0.82	0.031	< 0.001

BM body mass, *CMJ20* countermovement jump with 20 kg external load, *DJ35* drop jump from 35 cm height, *DJ50* drop jump from 50 cm height, *GCT* ground contact time, *JH* jump height, *P* power, *RSI* reactive strength index, *SJ* squat jump, *1RM* one-repetition maximum

$*P < 0.05$ for all R^2 and adjusted R^2 values

However, it concurs with those by Kale et al. [15] and McCurdy et al. [23] as weaker correlations were seen between SLJ and sprint performance (Fig. 2). It is conceivable that SLJ could be influenced by technical execution and coordination, and anthropometrical differences such as leg length and body mass. The participants in the current study had heights ranging from 1.57 to 1.87 m and body mass from 51 to 73 kg, and their "relatively small stature" may have possibly influenced SLJ performance. When normalisation was performed on SLJ data by dividing distance jumped by body height, correlation coefficients between SLJ and sprint times for different distances improved (e.g., from small to moderate) but were still not significant (Fig. 2).

The influence of maximal strength on sprint performance for different sports has been previously investigated [1, 6, 35], but results have not been always positive [7]. The present study revealed that the contributions of maximal strength was more important for sprint phases reaching maximal velocity. Relative strength during maximal back-squat was significantly related to 60 m, 10–30 m, and 30–60 m sprint performances ($r = -0.49$ to -0.53), but only achieved moderate and non-significant associations with distances that required high acceleration actions such as 10 m and 30 m sprints from a block start (Fig. 2). This was surprising as high acceleration can be achieved through large exertion of horizontal force on the ground [14]. Such observation may be partly linked to insufficient strength level and/or poor technical execution of the athletes, which limits the ability to accelerate. However, similar results were also observed in other studies that utilised a more homogenous groups, such as samples of similar sports/events, training history, and gender [1, 7, 27].

Generally, lower correlation coefficients were found between maximal strength measures with sprint performance, compared to vertical jumps (Table 2; Figs. 1, 2). Such outcomes could be attributed to the limited common variance between the two exercises, which utilise different strength qualities [7]. Irrespective of exercise, a vertical jump exercise is ballistic in nature and performed with continued acceleration without the need to decelerate at the end of the range of motion [26] but this does not occur during the maximal squat exercise. Lower mechanical power is produced when exercising with higher loads, whilst high-speed movements are required to produce high mechanical power [15]. The explosive nature of vertical jumps could have provided a higher common variance to sprinting. Additionally, both absolute and relative strength appear necessary to predict sprint performance, especially when they are combined with at least one explosive task (e.g., SJ) (Table 3).

Based on the regression model (Table 3), one of the most important findings is that different SJ parameters (height or relative peak power) were able to consistently predict sprint performance for all sprint distances especially when combined with other vertical jump and/or strength parameters (Table 3). Furthermore, linear regression analysis showed that SJ height and relative squat strength explained 75% of the variance in the 60 m sprint. Previous studies found that JH during SJ and CMJ, in addition with the DJ height and

Table 4 Comparisons of sprint times, loaded and unloaded vertical jumps, 1RM squat loads, and standing long jump distances between SSG and FSG (mean ± standard deviation)

	All ($n=18$)	SSG ($n=9$)	FSG ($n=9$)	*P* value	ES 90% (CI), descriptor
Sprint performance					
10 m (s)	1.61 ± 0.06	**1.63 ± 0.03**	**1.58 ± 0.07**	**0.041***	− 0.85 (− 1.12, − 0.59), L
30 m (s)	3.76 ± 0.09	**3.82 ± 0.05**	**3.70 ± 0.08**	**0.003***	− 1.37 (− 1.66, − 1.08), L
60 m (s)	6.73 ± 0.15	**6.84 ± 0.10**	**6.62 ± 0.11**	**0.001***	− 1.70 (− 2.00, − 1.40), L
10–30 m flying (s)	2.16 ± 0.05	**2.18 ± 0.04**	**2.13 ± 0.03**	**0.002***	− 1.62 (− 1.91, − 1.32), L
30–60 m flying (s)	2.97 ± 0.07	**3.02 ± 0.05**	**2.91 ± 0.05**	**0.001***	− 1.64 (− 1.93, − 1.34), L
Squat jump					
F_{PEAK} (N)	1619 ± 145	1595 ± 82	1643 ± 191	0.493	0.28 (0.02, 0.54), S
P_{PEAK} (W)	4135 ± 374	4054 ± 232	4216 ± 479	0.376	0.38 (0.12, 0.65), S
JH (m)	0.46 ± 0.04	**0.44 ± 0.04**	**0.48 ± 0.03**	**0.030***	1.07 (0.80, 1.35), L
Relative F_{PEAK} (N/kg)	24.5 ± 1.7	**23.5 ± 1.4**	**25.5 ± 1.4**	**0.010***	1.25 (0.97, 1.54), L
Relative P_{PEAK} (W/kg)	62.7 ± 5.4	**59.9 ± 4.9**	**65.5 ± 4.5**	**0.023***	1.11 (0.83, 1.38), L
Countermovement jump					
F_{PEAK} (N)	1808 ± 260	1813 ± 93	1803 ± 368	0.939	− 0.03 (− 0.29, 0.23), T
P_{PEAK} (W)	4224 ± 412	4164 ± 274	4285 ± 526	0.549	0.26 (0.00, 0.52), S
JH (m)	0.51 ± 0.05	0.49 ± 0.05	0.53 ± 0.05	0.179	0.65 (0.38, 0.91), M
Relative F_{PEAK} (N/kg)	27.3 ± 3.0	26.8 ± 1.9	27.8 ± 3.9	0.485	0.29 (0.03, 0.55), S
Relative P_{PEAK} (W/kg)	64.0 ± 5.6	**61.4 ± 4.8**	**66.6 ± 5.3**	**0.047***	0.89 (0.62, 1.16), L
Loaded squat jump					
F_{PEAK} (N)	1773 ± 195	1781 ± 165	1765 ± 230	0.867	− 0.07 (− 0.33, 0.18), T
P_{PEAK} (W)	4068 ± 373	4064 ± 306	4073 ± 449	0.962	0.02 (− 0.24, 0.28), T
JH (m)	0.33 ± 0.03	0.33 ± 0.04	0.33 ± 0.02	0.637	0.24 (− 0.01, 0.50), S
Relative F_{PEAK} (N/kg)	26.8 ± 2.7	26.5 ± 2.3	27.1 ± 3.4	0.387	0.40 (0.14, 0.66), S
Relative P_{PEAK} (W/kg)	61.6 ± 4.9	60.0 ± 4.5	63.2 ± 5.0	0.155	0.66 (0.39, 0.92), M
Loaded countermovement jump					
F_{PEAK} (N)	1977 ± 227	1985 ± 152	1969 ± 293	0.885	− 0.06 (− 0.32, 0.20), T
P_{PEAK} (W)	4146 ± 351	4071 ± 225	4221 ± 446	0.381	0.38 (0.12, 0.64), S
JH (m)	0.36 ± 0.03	0.35 ± 0.03	0.37 ± 0.03	0.362	0.42 (0.16, 0.68), S
Relative F_{PEAK} (N/kg)	29.9 ± 2.4	29.2 ± 1.7	30.5 ± 2.8	0.263	0.46 (0.20, 0.72), L
Relative P_{PEAK} (W/kg)	61.2 ± 8.7	60.0 ± 3.2	62.4 ± 12.1	0.584	0.22 (− 0.04, 0.48), S
Drop jump (35 cm)					
GCT (s)	0.153 ± 0.02	0.162 ± 0.03	0.145 ± 0.02	0.130	− 0.85 (− 1.12, − 0.58), L
FT (s)	0.50 ± 0.04	**0.47 ± 0.03**	**0.52 ± 0.04**	**0.007***	1.22 (0.94, 1.51), L
JH (m)	0.31 ± 0.05	**0.28 ± 0.03**	**0.34 ± 0.05**	**0.010***	1.17 (0.89, 1.44), L
RSI (A.U)	2.03 ± 0.46	**1.74 ± 0.30**	**2.31 ± 0.42**	**0.004***	1.29 (1.01, 1.58), L
Drop jump (50 cm)					
GCT (s)	0.156 ± 0.02	0.162 ± 0.02	0.149 ± 0.02	0.128	− 0.76 (− 1.03, − 0.49), M
FT (s)	0.50 ± 0.05	0.48 ± 0.04	0.51 ± 0.05	0.109	0.72 (0.45, 0.98), M
JH (m)	0.30 ± 0.06	0.28 ± 0.04	0.33 ± 0.07	0.119	0.70 (0.43, 0.96), M
RSI (A.U)	1.98 ± 0.50	1.76 ± 0.47	2.20 ± 0.57	0.060	0.81 (0.54, 1.08), L
Strength					
1RM squat (kg)	120 ± 19	114 ± 22	126 ± 14	0.207	0.67 (0.40, 0.93), M
1RM/BM squat (kg/kg)	1.82 ± 0.31	**1.68 ± 0.26**	**1.96 ± 0.07**	**0.049***	1.02 0.75, 1.30), L
Horizontal jump					
SLJ (m)	2.79 ± 0.13	2.75 ± 0.14	2.83 ± 0.13	0.205	0.61 (− 0.56, 0.04), M
SLJ/stature (m/m)	1.62 ± 0.11	1.58 ± 0.12	1.67 ± 0.13	0.378	0.72 (0.45, 0.99), M

SSG slow-sprint group, *FSG* fast-sprint group, *F* force, *P* power, *JH* jump height, *BM* body mass, *GCT* ground contact time, *FT* flight time, *RSI* reactive strength index, *1RM* one-repetition maximum, *BM* body mass, *SLJ* standing long jump, *T* trivial, *S* small, *M* moderate, *L* large, *ES* effect size, *CI* confidence interval

*Significant at $P < 0.05$ (bolded)

RSI explained 63% ($r=0.840$) of velocities for different sprint phases [29], and also that a 5-step horizontal jump, and knee and ankle isokinetic flexion accounted for 83% of the variance in a 40 m sprint among athletes who were involved in sprint type sports [25]. Although these regression analyses did not utilise similar measures, the general outcomes can help provide better insight into the different strength qualities that support sprint performance.

As stated earlier, an important objective of this study was to examine if strength metrics could differentiate between faster and slower sprinters. Data analyses found that SJ height, relative SJ (F_{PEAK} and P_{PEAK}), relative CMJ (P_{PEAK}), and DJ (FT, JH, and RSI) from 35 cm were able to be distinguished between SSG and FSG (Table 4). DJ50 RSI was also seen to differentiate between SSG and FSG with a large magnitude of difference, and approached significance (Table 4). Reinforcing the current data is a study [4] that found CMJ and DJ parameters to discriminate well between faster (100 m time ~ 10.66 s) and slower (~ 10.96 s) athletes. The variables above discriminated between SSG and FSG are all associated with strength, which has been denoted as being the dominant quality for improvement of rates of force development and power [11, 28, 30, 31]. This clarified why faster individuals are able to produce force rapidly, while exerting higher ground reaction force and propulsive impulse during each foot strike that promotes faster sprinting [14, 35].

A concurrent difference in explosive qualities, in favour FSG was certainly observed in this study (Table 4), which highlights their significance for sprint performance. Such observation highlights the contribution of relative maximal-strength that underpins these qualities [28, 30, 31]. However, what has not been determined is how much strength is necessary to improve sprint performance, especially in this group of young sprinters. Data indicated a large magnitude of difference (~ 17%) in relative strength during the back-squat exercise between the two cohorts, with strength indices (strength-to-weight ratio) ranging between 1.31 to 2.16 for SSG, and 1.79 to 2.51 for FSG (Table 4). A further analysis with the five fastest sprinters (100 m: 10.18–10.48 s) revealed relative strength indices ranging from 1.80 to 2.12, while the five slowest sprinters (100 m: 11.00–11.14 s) had indices of 1.31–1.96. This illustrates that relative strength data seems practical for distinguishing sprint ability levels and that these indices are indicative of different sprint ability among young male sprinters.

The current study has strengths and limitations. The athletes studied were young elite sprinters, and likely provided normative values for athletes and coaches when training to improve sprint performance. Nonetheless, correlation does not imply causal and effect, it means that improvement in vertical jump or maximal strength may or may not result in an improved sprint performance. Longitudinal investigation is therefore warranted to observe if positive changes in vertical jump or strength would transfer positively to sprint performance.

Conclusions

Vertical jumps are simple, and are frequently utilised during training, testing and monitoring of elite athletes. Our findings support the use of ballistic movements such as the vertical jump to assess and enhance sprint performance. Furthermore, a combination of various measures of explosive performance may provide additional insight regarding factors that enhance sprint performance, while cognisant of the importance of relative strength. While we note the importance of loaded jumps to improve mechanical power, coaches and practitioners should be aware that many typical parameters of vertical jumps (e.g., P_{PEAK}, F_{PEAK}, and JH) are more meaningful when obtained during unloaded jumps. Similarly, DJ (of drop height not more than 35 cm) could also provide essential information to improve sprint performance. Neuromuscular abilities, physiological capacities, and performance profiles may be reflective of training content history of an athlete. Therefore, coaches should emphasise the development of explosive power and reactive strength, along with adequate maximal-strength to improve acceleration and maximal speed performance in young male elite-sprinters.

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Author Contributions JAW conceived the ideas and design, acquisition of data, carried out the experiments and analysis, interpretation of data, drafted the manuscript, critical revision of the manuscript, and final quality check of the manuscript. L-YK carried out further analysis, interpretation of data, critical revision of the manuscript, and final quality check of the manuscript.

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Data Availability Available from the corresponding author, upon a reasonable request.

Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical Approval Approved by the Institutional Ethics Committee of the National Sports Institute of Malaysia.

Consent to Participate All participants consented (in written statement) to undertake all procedures related to this project.

Consent for Publication Participants consented the publication of data (which are presented anonymously).

References

1. Baker D, Nance S. The relation between running speed and measures of strength and power in professional rugby league players. J Strength Cond Res. 1999;13(3):230–5.
2. Barr MJ, Nolte VW. Which measure of drop jump performance best predicts sprinting speed? J Strength Cond Res. 2011;25(7):1976–82.
3. Bosco C, Luhtanen P, Komi PV. A simple method for measurement of mechanical power in jumping. Eur J Appl Physiol Occup Physiol. 1983;50(2):273–82.
4. Coh M, Mackala K. Differences between elite and sub-elite sprinters in kinematic and dynamic determinations of countermovement jump and drop jump. J Strength Cond Res. 2013;27(11):3021–7.
5. Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale: Lawrence Earlbaum Associates; 1988.
6. Comfort P, Stewart A, Bloom L, Clarkson B. Relationships between strength, sprint, and jump performance in well-trained youth soccer players. J Strength Cond Res. 2014;28(1):173–7.
7. Cronin JB, Hansen KT. Strength and power predictors of sports speed. J Strength Cond Res. 2005;19(2):349–57.
8. Dobbs CW, Gill ND, Smart DJ, McGuigan MR. Relationship between vertical and horizontal jump variables and muscular performance in athletes. J Strength Cond Res. 2015;29(3):661–71.
9. Epley B. Poundage chart. Boyd Epley workout. Lincoln NE: Body Enterprises; 1985. p. 86.
10. Fleiss JL. The design and analysis of clinical experiments. New York: John Wiley & Sons; 1986.
11. Haff GG, Nimphius S. Training principles for power. Strength Cond J. 2012;34:2–12.
12. Hennessy L, Kilty J. Relationship of the stretch-shortening cycle to sprint performance in trained female athletes. J Strength Cond Res. 2001;15(3):326–31.
13. Hopkins WB, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009;41(1):3–12.
14. Hunter JP, Marshall RN, McNair PJ. Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. J Appl Biomec. 2005;21(1):31–43.
15. Kale M, Asci A, Bayrak C, Acikada C. Relationships among jumping performances and sprint parameters during maximum speed phase in sprinters. J Strength Cond Res. 2009;23(8):2272–9.
16. Kariyama Y, Zushi K. Relationships between lower-limb joint kinetic parameters of sprint running and rebound jump during the support phases. J Phys Fitness Sports Med. 2016;5(2):187–93.
17. Krell JB, Stefanyshyn DJ. The relationship between extension of the metatarsophalangeal joint and sprint time for 100m Olympic athletes. J Sports Sci. 2006;24(2):175–80.
18. Lacour R. Physiological analysis of qualities required in sprinting. N Stud Athletics. 1996;11:59–62.
19. Loturco I, D'Angelo RA, Fernandes V, Gil S, Kobal R, Cal Abad CC, Kitamura K, Nakamura FY. Relationship between sprint ability and loaded/unloaded jump tests in elite sprinters. J Strength Cond Res. 2015;29(3):758–64.
20. Loturco I, Pereira LA, Cal Abad CC, D'Angelo RA, Fernandes V, Kitamura K, Kobal R, Nakamura FY. Vertical and horizontal jump tests are strongly associated with competitive performance in 100-m dash events. J Strength Cond Res. 2015;29(7):1966–71.
21. Loturco I, Kobal R, Kitamura K, Fernandes V, Moura N, Siqueira F, Cal Abad CC, Pereira LA. Predictive factors of elite sprint performance: influences of muscle mechanical properties and functional parameters. J Strength Cond Res. 2019;33(4):974–86.
22. Markstrom JL, Olsson CJ. Countermovement jump peak force relative to body weight and jump height as predictors for sprint running performances: (in)homogeneity of track and field athletes? J Strength Cond Res. 2013;27(4):944–53.
23. McCurdy KW, Walker JL, Langford GA, Kutz MR, Guerrero JM, McMillan J. The relationship between kinematic determinants of jump and sprint performance in division i women soccer players. J Strength Cond Res. 2010;24(12):3200–8.
24. Nagahara R, Matsubayashi T, Matsuo A, Zushi K. Kinematics of transition during human accelerated sprinting. Biol Open. 2014;3(8):689–99.
25. Nesser TW, Latin RW, Berg K, Prentice E. Physiological determinants of 40-meter sprint performance in young male athletes. J Strength Cond Res. 1996;10(4):263–7.
26. Newton RU, Kraemer WJ, Hakkinen KWJ, Hakkinen K. Kinematics, kinetics and muscle activation during explosive upper body movements. J Appl Biomech. 1996;12(1):31–43.
27. Requena B, Garcia I, Requena F, de Villarreal ES, Cronin JB. Relationship between traditional and ballistic squat exercise with vertical jumping and maximal sprinting. J Strength Cond Res. 2011;25(8):2193–204.
28. Schmidtbleicher D. Training for power events. In: Komi PV, editor. Strength and power in sport. Boston: Blackwell Scientific; 1992. p. 381–95.
29. Smirniotou A, Katsikas C, Paradisis G, Argeitaki P, Zacharogiannis E, Tziortzis S. Strength-power parameters as predictors of sprinting performance. J Sports Med Phys Fit. 2008;48(4):447–54.
30. Stone MH, Moir G, Glaister M, Sanders R. How much strength is necessary? Phys Ther Sport. 2002;3(2):88–96.
31. Suchomel TJ, Nimphius S, Stone MH. The importance of muscular strength in athletic performance. Sports Med. 2016;46(10):1419–49.
32. Swinton PA, Lloyd R, Keogh JWL, Agouris I, Stewart AD. Regression models of sprint, vertical jump, and change of direction performance. J Strength Cond Res. 2014;28(7):1839–48.
33. Washif JA, Kok LY. The reactive bounding coefficient as a measure of horizontal reactive strength to evaluate stretch-shortening cycle performance in sprinters. J Hum Kinet. 2020;21(73):45–55.
34. Washif JA. Does whole-body vibration potentiate reactive strength performance in sprinters? J Aust Strength Cond. 2019;27(7):14–22.
35. Weyand PG, Sternlight DB, Bellizzi MJ, Wright S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. J Appl Physiol. 2000;89(5):1991–9.
36. Wild J, Bezodis NE, Blagrove R, Bezodis IA. Biomechanical comparison of accelerative and maximum velocity sprinting: specific strength training considerations. Prof Strength Cond. 2011;21:23–37.
37. Young W, McLean B, Ardagna J. Relationship between strength qualities and sprinting performance. J Sports Med Phys Fitness. 1995;35:13–9.