INFLUENCE OF REACTIVE AND MAXIMUM STRENGTH INDICATORS ON SPRINT PERFORMANCE

Robin Healy, Carol Smyth, Ian C. Kenny, Andrew J. Harrison.

Department of Physical Education and Sport Sciences, University of Limerick, Ireland.

Robin Healy

Biomechanics Research Unit

Department of Physical Education & Sport Sciences

University of Limerick

Ireland

Email: robin.healy@ul.ie / rhealy@ait.ie

Healy, R., Smyth, C., Kenny, I.C., and Harrison, A.J. (2018) 'Influence of reactive and maximum strength performance indicators on sprint performance. *Journal of Strength and Conditioning Research*. [Epub ahead of print] (DOI: 10.1519/JSC.0000000000002635).

ABSTRACT

The primary aim of this study was to assess the relationship between reactive and maximal strength measures with 40 m sprint performance and mechanical properties. Fourteen male and fourteen female sprinters participated in this study. On the first day subjects performed 40 m sprints with 10 m split times recorded in addition to maximal theoretical velocity, maximal theoretical force and peak horizontal power which were calculated from force-velocity relationships. On the second day subjects performed isometric mid-thigh pulls (IMTP) with peak force and relative peak force calculated, drop jumps and vertical hopping where the reactive strength index (RSI) was calculated as jump height (JH) divided by contact time (CT). Pearson correlations were used to assess the relationships between measures and independent samples t-tests were used to assess the differences between men and women. No significant correlations were found between drop jump and hopping RSI and sprint measures. A significant strong positive correlation was found between IMTP peak force and peak horizontal power in men only (r = 0.61). The male sprinters performed significantly better in all recorded measures apart from hopping (CT, JH and RSI) and drop jump CT where no significant differences were found. The lack of association between reactive and maximal strength measures with sprint performance are potentially due to the test's prolonged CTs relative to sprinting and the inability to assess the technical application of force. Several methods of assessing reactive strength are needed that can better represent the demands of the distinct phases of sprinting e.g. acceleration, maximum velocity.

KEY WORDS: drop jump, hopping, isometric mid-thigh pull, stretch shortening cycle, contact time, force-velocity profiling.

INTRODUCTION

Sprint performance is critical to success in various team and individual sports. In track events, rapid acceleration and high maximum velocity are crucial to race performance (20, 35). The 100 m sprint can be broken down simply, into three main phases: the acceleration phase, the maximum velocity phase and the deceleration phase (9). Furthermore, each phase can be sub-divided in various ways e.g. the initial acceleration phase (0-12 m) and the main acceleration phase (12-35 m) (21). Consequently, sprinting can be considered a multidimensional skill with different kinematic and kinetic requirements during the distinct phases (9). Accordingly, different strength capabilities play relatively larger roles throughout the performance of a sprint (26).

A novel field method of profiling athletes' horizontal force-velocity relationship over 40 m has recently been developed (32). Mechanical variables such as the theoretical maximum horizontal component of ground reaction force (F_0), theoretical maximum horizontal velocity (v_0) and the maximum horizontal mechanical power (P_{max}) produced can all be measured during accelerative performance (32). Research on sprint athletes has found that maximum velocity and mean 100 m velocity were both very strongly correlated with P_{max} (23). In contrast, Slawinski et al. (35) found no correlation between P_{max} and 100 m time, whereas v_0 had a very large negative correlation with P_{max} in world class athletes. It is suggested that P_{max} may be more likely related to performance over shorter distances i.e. 40 or 60 m where fatigue is limited (35). This is supported by Rabita et al. (28) who found that maximal velocity achieved over 40 m and 40 m performance in elite and sub elite sprinters had an almost perfect positive and very large positive correlation with P_{max} and v_0 respectively.

The ground contact phase of sprinting involves the coupling of an eccentric contraction with a concentric contraction. This is termed the stretch shortening cycle (SSC) and it is frequently used in many additional sports movements; e.g. in the leg extensor muscles during jumping and hopping (27). The SSC has been classified as either fast, where contact times (CTs) < 0.250 s, or slow, where CTs > 0.250 s (34). Therefore, sprinting is considered a fast SSC activity as a sprinter's CT after the initial block push off, is below 0.250 s for each step with CTs progressively decreasing throughout the acceleration phase with values as low as ~0.090-0.120 s reported at maximum velocity (8, 19). Traditionally, fast SSC performance has been assessed through the measurement of the reactive strength index (RSI) which is usually calculated by dividing the jump height by the contact time in a specific jump (45). The RSI has been assessed during drop jumps, rebound jumps and ankle jumps (hopping) (13, 26, 46).

The association between RSI and sprint performance in sprint athletes has been previously studied with contrasting results. Young et al. (46) found no relationship between 2.5 m and 50 m sprint times and drop jump RSI in male and female sprinters. In contrast, Hennessy and Kilty (15) found very large negative correlations between sprint times over 30 m and 100 m and RSI in female sprinters. Furthermore, Smirniotou et al. (36) found moderate to large negative correlations between sprint performances over 10, 30, 60 and 100 m and drop jump RSI in male sprinters. Nagahara et al. (26) assessed RSI during rebound jumps (termed the "rebound jump index") and bilateral vertical hops (termed the "ankle jump index") along with sprint time and individual step acceleration over 60 m. Although rebound jump RSI was not related to any of the sprint measures, hop RSI had a moderate negative relationship with 60 m time and a moderate to large positive relationship with step acceleration over the 23 – 34 m interval. Additionally, Nagahara et al. (26) found no relationship between rebound jump RSI and hop RSI. The relationship between hop RSI and drop jump RSI has yet to be assessed. This warrants investigation as Hop RSI may provide coaches with an additional insight into the reactive strength capabilities of their athletes.

Sprinting requires the production of very large forces over very short time periods. Consequently, sprint coaches utilize a variety of training modalities to develop different strength qualities; these may include reactive strength and maximum strength training performed throughout the training cycle (5). Maximum strength has been defined as the ability to voluntarily generate maximal force under specified conditions (29). Strength tests such as the back squat and isometric squat have previously been used with sprint athletes with very strong negative correlations found between relative 1RM and 100 m time (22) and between peak force (PF) and maximum velocity (46). The isometric mid-thigh pull (IMTP) has become a popular method of assessing maximum strength as the peak force applied during the pull can be measured directly from a force platform. Several authors have assessed peak force and relative peak force measured in an IMTP with sprint performance in team sport athletes with contrasting results. Significant relationships have been found between PF and 5 and 20 m times (39) and between relative PF and 10 m time (41, 42). Wang et al. (41) however, found no relationship was found between PF and short sprint performance (5 m and

10 m). It is not currently known whether stronger sprint athletes, as measured by the IMTP, produce higher levels of maximal mechanical power or apply greater maximal theoretical horizontal forces during a sprint.

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

METHODS

Experimental Approach to the Problem

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

Subjects

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

40 m Sprint Testing

Following an individualized, race specific warm up, lasting ~30 minutes, athletes completed three maximal effort 40 m sprints from a block start with the first trial acting as a familiarization trial. Six minutes of recovery time were provided with additional time granted if requested. To ensure athletes continued sprinting at maximal effort for the entire 40 m, coloured cones were placed at 45 m and athletes were instructed not to begin their deceleration until they had passed the cones. Racetime 2, dual-beam timing gates (Microgate, Bolzano, Italy) were positioned at 10 m, 15 m, 20 m, 30 m and 40 m. Split times from 0-10 m, 10-20 m, 30-40 m, and overall 40 m were recorded in addition to maximal velocity which was calculated as the fastest 10 m split time divided by 10. Timing was initiated at the instant the athlete's hand left the track surface using a previously validated protocol which synchronised timing gates to the Optojump™ system which is an optical measuring unit (14). This protocol enabled the measurement of the true 10 m movement time.

In addition to sprint performance measures, sprint mechanical properties were calculated based on the five timing gate split times using the methods of Samozino et al. (32). The horizontal velocity of the center of mass (v_h) versus time (t) curve was modelled using a mono-exponential function (32):

$$v_h(t) = v_{hmax} \cdot (1 - e^{-t/\tau}) \qquad \text{Eq. 1.}$$

where, v_{hmax} is the maximal velocity, t is the time and τ is the acceleration time constant which represents the ratio of maximal velocity to maximal acceleration. By integrating equation 1, an equation for the horizontal position of the center of mass can be derived:

$$x_h(t) = v_{hmax} \cdot \left(t + \tau \cdot e^{-\frac{t}{\tau}}\right) - v_{hmax} \cdot \tau \qquad \text{Eq. 2.}$$

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

$$a_h(t) = \left(\frac{v_{hmax}}{\tau}\right) \cdot e^{-\frac{t}{\tau}} \qquad \text{Eq. 3.}$$

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

$$F_h(t) = m \cdot a_h(t) + F_{aero}(t) \qquad \text{Eq. 4.}$$

Where m is the body mass of the sprinter and F_{aero} (t) is the estimated aerodynamic drag force the sprinter experienced throughout the sprint (2, 32, 40). The maximal theoretical horizontal velocity (v_0) and maximal theoretical horizontal force (F_0) were calculated as the x and y intercept of the individual force-velocity relationships, determined via least squares regression, respectively (24, 32). The F_0 represents the maximal theoretical horizontal force applied by the athlete at the initial push i.e. when velocity is zero. The v_0 represents the maximal theoretical horizontal velocity of the athlete if net internal and external mechanical resistances, such as drag, were null (24, 32). The maximum mechanical power developed in the horizontal direction (P_{max}) was calculated using the following equation validated by previous work (31, 33):

$$P_{max} = \frac{F0 \cdot v0}{4} \qquad \text{Eq. 5.}$$

Both F_0 and P_{max} were expressed relative to body mass.

Isometric Mid-Thigh Pull

A specific IMTP warm up, consisting of pulling the IMTP bar at an intensity of 50%, 70% and 90% for a period of five seconds, was performed by each athlete (4). The height of the

IMTP bar was set individually so that each athlete could adopt the second pull position of the clean with an upright trunk and knee angle ~130-140º (12, 38). Following the warm up, athletes performed two maximal effort pulls separated by 3 minutes of rest. Athletes were instructed to adopt the second pull position and on the experimenter's verbal command of "GO!", to pull as hard and as fast as possible for the full five seconds (12). IMTP testing was conducted with a custom-made isometric rack (Odin, Ireland) that enabled the placement of a steel bar at intervals of 50 mm. The rack was anchored to the laboratory floor and placed over two AMTI force platforms (Advanced Mechanical Technologies, MA, USA) operating at 1,000 Hz. PF was calculated directly from the force-time curve as the maximum force produced during each five second trial. Relative PF was also calculated by dividing PF by the athlete's mass.

Drop Jumps

Following a standardised dynamic warm up, athletes performed three maximal effort drop jumps with the first jump serving as a practice trial and the two subsequent jumps retained for analysis. Athletes were instructed to keep their hands on their hips throughout the entire movement, to step directly off of the box i.e. avoid stepping down from the box or jumping off of the box, avoid any tucking motion in the air and to attempt to land in the same position as take-off. Additionally, athletes were instructed to aim to minimise CT while also trying to maximise JH during each jump (45). All drop jumps were visually assessed by the experimenter and trials were repeated if any of the instructions were not correctly followed or if CT > 0.250 s. Thirty seconds of rest were provided between trials to avoid any deleterious effects of fatigue on performance. Drop jumps were performed from a box height of 0.3 m with athletes landing on a force platform operating at 1,000 Hz.

The dependent variables calculated were: CT, JH and RSI. CTs were obtained directly from the force-time trace using a threshold of >10 N to determine contact and <10 N to determine flight. Flight time i.e. the time elapsed between the initiation of the flight phase and the subsequent contact phase was used to estimate JH using an adapted version of the second mathematical equation of linear motion i.e. $JH = FT^2 \times 1.22625$. RSI was calculated as JH divided by CT (45). The trial with the highest RSI was considered the best trial and was used for the final analysis.

Hopping Test

For the hopping test, participants performed two trials of a 10 s hopping test at a frequency of 2.2 Hz. A 2.2 Hz hopping frequency was chosen as this frequency elicits shorter CTs and greater ankle stiffness compared to unconstrained hopping and hopping at lower frequencies e.g. 1.5 Hz (10, 16, 25). The hopping frequency was imposed via a metronome operating at 132 beats per minute. Participants were instructed: to land on the audible tone of the metronome, in the same position as take-off, to keep their hands on their hips throughout and to keep their legs as straight as possible by trying to avoid knee and hip flexion as much as possible (26). All trials were visually assessed by the same investigator to ensure consistent technique and remove invalid trials (i.e. where participants did not land on the force platform or took their hands off their hips). Similar to previous investigations, only hops that were performed within 2% (2.16 – 2.24 Hz) of the desired hopping frequency were included in the analysis (11). Similar to the ten to five repeated jump test, the five best hops, as determined by the highest RSIs, in each trial were used to calculate average values for CT, JH and RSI (13). Dependent variables were calculated using the same methods described for the drop jumps.

Statistical Analyses

All variables were found to be normally distributed as the Shapiro-Wilk's test had an alpha level > 0.05. Descriptive statistics for all variables were presented as mean ± SD. The test-retest reliability of each variable was assessed by calculating the single measure intraclass correlation coefficient (ICC) with 95% CI and the typical error, expressed as a coefficient of variation (CV%) (18).

Differences between men and women were assessed using independent samples t-tests and Cohen's d effect size (ES) was used to assess the magnitude of differences between groups. The absolute value of the effect sizes were interpreted as trivial (ES < 0.2), small (0.2 ≤ ES < 0.6), moderate (0.6 ≤ ES < 1.2), large (1.2 ≤ ES < 2) very large (2 ≤ ES < 4) and extremely large (> 4) according to the scale proposed by Hopkins et al. (17).

Relationships between sprint, reactive strength and maximal strength measures were determined using Pearson's product moment correlation with the alpha level set at 0.05. The strength of the correlations was evaluated as: trivial (0 – 0.09), small (0.1 – 0.29), moderate (0.3 – 0.49), large (0.5 – 0.69), very large (0.7 – 0.89), near perfect (0.9 – 0.99) and perfect

(1) (17). Non-significant correlations were not interpreted. All statistical analyses apart from the CV% were performed using SPSS software (version 21.0, SPSS, Inc., IL, USA).

RESULTS

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

Table 1: Test-retest single measure intraclass correlation coefficient with 95% CI and CV% for sprint, hop, drop jump and isometric mid-thigh pull for men and women.

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

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

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

PF = Peak force, Rel PF = Peak force relative to body mass.

Table 2: Mean ± SD, mean difference with 95% CI, Cohen's d effect size and magnitude for sprint, drop jump, hop and isometric mid-thigh pull.

	Men	Women	Mean Difference (95% CI)	*p Value*	Effect Size (95% CI)	Magnitude
0-10 m (s)	1.90 ± 0.05	2.11 ± 0.10	-0.21 (-0.28 to -0.15)	**< 0.001****	-2.60 (-3.40 to -1.81)	Very large
10-20 m (s)	1.18 ± 0.04	1.32 ± 0.06	-0.15 (-0.18 to -0.11)	**< 0.001****	-3.08 (-3.86 to -2.30)	Very large
20-30 m (s)	1.09 ± 0.03	1.24 ± 0.06	-0.15 (-0.19 to -0.11)	**< 0.001****	-3.01 (-3.80 to -2.21)	Very large
30-40 m (s)	1.06 ± 0.05	1.23 ± 0.07	-0.17 (-0.21 to -0.12)	**< 0.001****	-2.66 (-3.45 to -1.88)	Very large
40 m (s)	5.22 ± 0.15	5.90 ± 0.29	-0.68 (-0.86 to -0.50)	**< 0.001****	-2.97 (-3.76 to -2.17)	Very large
Max Velocity (m.s^{-1})	9.49 ± 0.40	8.23 ± 0.46	1.26 (0.92 to 1.59)	**< 0.001****	-2.93 (-3.70 to -2.15)	Very large
F_0 (N/kg)	9.3 ± 0.5	8.0 ± 0.7	1.4 (0.9 to 1.9)	**< 0.001****	-2.14 (-2.92 to -1.36)	Very large
P_{max} (W·kg^{-1})	22.5 ± 2.6	16.4 ± 2.3	6.1 (4.2 to 8.0)	**< 0.001****	-2.50 (-3.28 to -1.72)	Very large
v_0 (m.s^{-1})	9.84 ± 0.40	8.51 ± 0.46	1.33 (1.00 to 1.67)	**< 0.001****	-3.12 (-3.89 to -2.34)	Very large
Hop CT (s)	0.157 ± 0.019	0.158 ± 0.015	-0.001 (-0.014 to 0.012)	0.885	-0.06 (-0.73 to 0.84)	Trivial
Hop JH (m)	0.111 ± 0.015	0.111 ± 0.010	0.000 (-0.010 to 0.010)	0.954	-0.02 (-0.76 to 0.81)	Trivial
Hop RSI (m.s^{-1})	0.72 ± 0.16	0.72 ± 0.13	0.00 (-0.11 to 0.11)	0.969	-0.01 (-0.79 to 0.76)	Trivial
DJ CT (s)	0.170 ± 0.028	0.183 ± 0.028	-0.013 (-0.035 to 0.008)	0.220	-0.47 (-1.25 to 0.30)	Small
DJ JH (m)	0.340 ± 0.049	0.296 ± 0.057	0.044 (0.003 to 0.086)	**0.038***	0.83 (0.05 to 1.60)	Moderate
DJ RSI (m.s^{-1})	2.06 ± 0.43	1.65 ± 0.35	0.41 (0.10 to 0.71)	**0.011***	1.04 (0.26 to 1.82)	Moderate
IMTP PF (N)	2642 ± 437	1913 ± 342	730 (425 to 1034)	**< 0.001****	1.86 (1.08 to 2.64)	Large
IMTP Relative PF (N·kg^{-1})	36.3 ± 6.2	29.8 ± 5.2	6.49 (2.0 to 10.9)	**0.006****	1.13 (0.35 to 1.91)	Moderate

F_0 = Maximal theoretical horizontal force relative to body mass, v_0 = Maximal theoretical horizontal velocity, CT = Contact time, JH = Jump height

RSI = Reactive strength index, DJ = drop jump, IMTP = Isometric mid-thigh pull, PF = Peak force, Relative PF = Peak force relative to body mass.

* p<0.05, ** p <0.01

Correlations between sprint performance variables and sprint mechanical properties and Hop RSI, DJ RSI, IMTP PF and IMTP relative PF and are shown in Table 3 and Table 4 respectively. No significant correlations were found between hop RSI, drop jump RSI, IMTP PF or relative PF and any of the sprint performance measures. A significant strong positive correlation was found between IMTP PF and relative P_{max} in men only.

Table 3: Inter-correlation matrix between drop jump and hop RSI, isometric mid-thigh pull PF and relative PF and sprint performance measures in men (top) and women (bottom). Results are presented as r (95% CI) with statistically significant correlations presented in bold.

Men						
	0-10 m (s)	10-20 m (s)	20-30 m (s)	30-40 m (s)	40 m (s)	Max Velocity ($m \cdot s^{-1}$)
Hop RSI ($m \cdot s^{-1}$)	-0.22 (-0.67 to 0.35)	-0.15 (-0.63 to 0.42)	-0.22 (-0.67 to 0.35)	-0.17 (-0.65 to 0.39)	-0.21 (-0.67 to 0.36)	0.22 (-0.35 to 0.67)
Drop Jump RSI ($m \cdot s^{-1}$)	-0.03 (-0.55 to 0.51)	0.01 (-0.52 to 0.54)	0.14 (-0.42 to 0.62)	-0.02 (-0.55 to 0.51)	0.02 (-0.52 to 0.54)	0.10 (-0.46 to 0.60)
IMTP PF (N)	-0.31 (-0.72 to 0.26)	-0.40 (-0.77 to 0.16)	-0.47 (-0.80 to 0.08)	-0.35 (-0.74 to 0.22)	-0.42 (-0.78 to 0.14)	0.30 (-0.27 to 0.72)
IMTP Rel PF ($N \cdot kg^{-1}$)	-0.31 (-0.72 to 0.26)	-0.29 (-0.71 to 0.29)	-0.24 (-0.68 to 0.34)	-0.22 (-0.67 to 0.35)	-0.30 (-0.71 to 0.28)	0.21 (-0.36 to 0.67)
Women						
	0-10 m (s)	10-20 m (s)	20-30 m (s)	30-40 m (s)	40 m (s)	Max Velocity ($m \cdot s^{-1}$)
Hop RSI ($m \cdot s^{-1}$)	-0.34 (-0.74 to 0.23)	-0.16 (-0.64 to 0.40)	-0.31 (-0.72 to 0.27)	-0.22 (-0.67 to 0.35)	-0.28 (-0.71 to 0.29)	0.27 (-0.30 to 0.70)
Drop Jump RSI ($m \cdot s^{-1}$)	-0.04 (-0.56 to 0.50)	0.21 (-0.36 to 0.67)	0.02 (-0.51 to 0.55)	0.04 (-0.50 to 0.56)	0.04 (-0.50 to 0.56)	-0.03 (-0.55 to 0.51)
IMTP PF (N)	0.30 (-0.27 to 0.72)	0.13 (-0.43 to 0.62)	0.29 (-0.29 to 0.71)	0.36 (-0.21 to 0.75)	0.29 (-0.28 to 0.71)	-0.36 (-0.75 to 0.21)
IMTP Rel PF ($N \cdot kg^{-1}$)	0.09 (-0.45 to 0.59)	0.01 (-0.52 to 0.54)	0.11 (-0.45 to 0.61)	0.28 (-0.30 to 0.71)	0.13 (-0.43 to 0.62)	-0.24 (-0.68 to 0.34

RSI = Reactive strength index, IMTP = Isometric mid-thigh pull,
PF = Peak force, Rel PF = Peak force relative to body mass.

Table 4: Inter-correlation matrix between drop jump and hop RSI, isometric mid-thigh pull PF and relative PF and sprint mechanical properties in men (top) and women (bottom).

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

	F_0 (N·kg^{-1})	P_{max} (W·kg^{-1})	v_0 (m·s^{-1})
Men			
Hop RSI (m·s^{-1})	0.07 (-0.48 to 0.58)	0.15 (-0.42 to 0.63)	0.24 (-0.34 to 0.68)
DJ RSI (m·s^{-1})	-0.11 (-0.60 to 0.45)	-0.23 (-0.68 to 0.34)	0.03 (-0.51 to 0.55)
IMTP PF (N)	0.23 (-0.34 to 0.68)	**0.61 (0.12 to 0.86)**	0.39 (-0.18 to 0.76)
IMTP Rel PF (N·kg^{-1})	0.24 (-0.33 to 0.69)	0.37 (-0.20 to 0.75)	0.24 (-0.33 to 0.68)
Women			
	F_0 (N·kg^{-1})	P_{max} (W·kg^{-1})	v_0 (m·s^{-1})
Hop RSI (m·s^{-1})	0.34 (-0.24 to 0.73)	0.32 (-0.25 to 0.73)	0.24 (-0.33 to 0.68)
DJ RSI (m·s^{-1})	0.03 (-0.51 to 0.55)	0.00 (-0.53 to 0.53)	0.07 (-0.48 to 0.58)
IMTP PF (N)	-0.13 (-0.62 to 0.43)	-0.27 (-0.70 to 0.31)	-0.33 (-0.73 to 0.24)
IMTP Rel PF (N·kg^{-1})	0.05 (-0.50 to 0.56)	-0.04 (-0.56 to 0.50)	-0.22 (-0.67 to 0.35)

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

The relationships between hop, DJ and IMTP measures for both men and women are shown in Table 5. DJ CT had a very large significant correlation with Hop CT, Hop JH and Hop RSI in men only. DJ RSI had a significant correlation with Hop CT (men: large negative, women: very large negative), Hop JH (men: large positive, women: very large positive) and Hop RSI (men and women: large positive). IMTP relative PF had a significant correlation with Hop CT (men: large negative), Hop JH (men: large positive) and Hop RSI (men: very large positive) and IMTP PF (men and women: very large positive).

Table 5: Inter-correlation matrix between hop, drop jump and IMTP measures in men (top) and women (bottom). Results are presented as r (95% CI) with statistically significant correlations presented in bold.

	DJ CT (s)	DJ JH (m)	DJ RSI ($m\cdot s^{-1}$)	IMTP PF (N)	IMTP Rel PF ($N\cdot kg^{-1}$)
Men					
Hop CT (s)	**0.84 (0.55 to 0.95)**	-0.19 (-0.65 to 0.38)	**-0.63 (-0.87 to -0.14)**	-0.39 (-0.76 to 0.18)	**-0.65 (-0.88 to -0.18)**
Hop JH (m)	**-0.77 (-0.92 to -0.39)**	0.24 (-0.33 to 0.68)	**0.63 (0.15 to 0.87)**	0.47 (-0.08 to 0.80)	**0.68 (0.23 to 0.89)**
Hop RSI ($m\cdot s^{-1}$)	**-0.77 (-0.92 to -0.41)**	0.19 (-0.38 to 0.66)	**0.62 (0.14 to 0.87)**	0.46 (-0.09 to 0.80)	**0.74 (0.34 to 0.91)**
IMTP PF (N)	0.01 (-0.52 to 0.54)	0.00 (-0.53 to 0.53)	-0.02 (-0.54 to 0.52)	1	**0.86 (0.60 to 0.95)**
IMTP Rel PF ($N\cdot kg^{-1}$)	-0.31 (-0.72 to 0.26)	0.19 (-0.38 to 0.66)	0.34 (-0.23 to 0.74)	**0.86 (0.60 to 0.95)**	1
Women					
	DJ CT (s)	DJ JH (m)	DJ RSI ($m\cdot s^{-1}$)	IMTP PF (N)	IMTP Rel PF ($N\cdot kg^{-1}$)
Hop CT (s)	0.50 (-0.05 to 0.81)	-0.46 (-0.79 to 0.1)	**-0.71 (-0.90 to -0.28)**	-0.30 (-0.71 to 0.28)	-0.53 (-0.83 to 0.00)
Hop JH (m)	-0.50 (-0.81 to 0.05)	0.47 (-0.08 to 0.80)	**0.72 (0.31 to 0.90)**	0.28 (-0.30 to 0.70)	0.45 (-0.11 to 0.79)
Hop RSI ($m\cdot s^{-1}$)	-0.42 (-0.78 to 0.14)	0.46 (-0.09 to 0.80)	**0.66 (0.20 to 0.88)**	0.33 (-0.25 to 0.73)	0.53 (0.00 to 0.83)
IMTP PF (N)	0.13 (-0.43 to 0.61)	0.28 (-0.30 to 0.70)	0.12 (-0.44 to 0.61)	1	**0.92 (0.77 to 0.98)**
IMTP Rel PF ($N\cdot kg^{-1}$)	-0.01 (-0.54 to 0.52)	0.40 (-0.16 to 0.77)	0.31 (-0.26 to 0.72)	**0.92 (0.77 to 0.98)**	1

CT = Contact time, JH = Jump Height, RSI = Reactive strength index, DJ = Drop jump

IMTP = Isometric mid-thigh pull, PF = Peak force, Rel PF = Peak force relative to body mass.

DISCUSSION

The present study found no significant relationships between drop jump RSI and sprint performance or sprint mechanical properties in both men and women. In contrast, research in male sprinters by Smirniotou et al. (37) and female sprinters by Hennessy and Kilty (15) found significant correlations with sprint acceleration performance over 10, 30 and 60 m. Young et al. (46) found no relationship with drop jump RSI and sprint performance over 2.5 m and 50 m. The authors, Young et al. (46), suggested that the sprint athletes studied may not have been able to tolerate the stretch loads imposed on them during the drop jump test. This may have been the case in the current study as evidenced by the large range of drop jump CTs (men: 0.137 - 0.249 s, women: 0.144 - 0.227 s) suggesting a wide range of stiffness capabilities (1). It is likely that drop jump RSI may therefore be a poor indicator of fast SSC performance in groups with wide ranging physical capacities i.e. leg spring stiffness. Additionally, the ground contact times of the drop jumps in the study were much larger than those observed during the acceleration (~0.130 s) and transition phase (0.110 – 0.119 s) in male and female sprint athletes of a similar level (8).

Similar to drop jumps, no significant relationship was found between hop RSI and any of the sprint performance or sprint mechanical variables. By contrast, Nagahara et al. (26), found a relationship between hop RSI and 60 m sprint time, but did not impose a set hopping frequency on the athletes. Previously, Chelly and Dennis, (6) used a set hopping frequency (2.0 Hz) and found a large positive correlation (r = 0.68) between stiffness and maximal sprinting velocity. Stiffness measures are considered indicative of an athlete's ability to tolerate stretch loads and thus achieve shorter CTs (1). The 2.2 Hz frequency used in the present study resulted in the hopping test becoming a sub-maximal reactive strength test as athletes limited their jump height in order to maintain the required hopping rhythm. For this reason, RSI measured in sub-maximal hopping would not reflect an athlete's true ability to generate an impulse and therefore constrained hopping is not recommended.

Neither of the IMTP measures was significantly related to any of the sprint performance measures. This is in contrast to Thomas et al. (39) and West et al. (42) who focused on short acceleration (20 m) but is in agreement with Wang et al. (41) who assessed longer sprints (40 m). Several key differences exist between those studies and the current study due to the different populations (sprinters versus team sport players) and different starting procedures used (block starts versus standing starts). A block start requires substantially greater technical ability in addition to the need to apply optimal levels of vertical and horizontal force (30). For the sprint mechanical properties, PF had a significant and large positive correlation with P_{max} in men with no other significant relationships found. While this may suggest that higher levels of absolute maximum strength may afford higher levels of horizontal power in sprinting, this is not supported by the results of the female group and therefore further research is required before a fully informed conclusion can be made.

It is important to note that all the strength tests used in this investigation were performed vertically with no horizontal component and this may partially explain the lack of significant findings in the current sprinter sample. Weyand et al. (44) found that faster maximum velocities were achieved predominantly through the application of greater vertical forces (relative to mass) on the ground at very short CTs (~0.100 s). Subsequent research by Weyand et al. (43) found that the stance phase limit to achieving higher maximum velocities is imposed by the minimum time required to apply great mass-specific forces and not the maximum force the limb can apply to the ground. Consequently, the duration of contact phases during sprinting are not long enough for maximal force production by the lower limb extensor muscles. The durations of force production in drop jumps, hopping and especially in the IMTP were considerably longer than those observed at high velocity sprinting.

The ability to effectively direct the horizontal component of GRF has been shown to be a key factor in sprint performance. Morin et al. (23) found that the magnitude of the resultant force was not related to 100 m performance but the ability to direct the action force backwards against the ground i.e. horizontal force application, was important. In accordance with this, Rabita et al. (28) found that neither the resultant GRF nor the vertical component were significantly correlated to sprint performance over 40 m. The authors suggested that the ability to generate high net horizontal force at high velocity was more important for sprint acceleration than simply increasing the magnitude of the resultant GRF. The maximal strength and reactive strength tests in the current study did not examine the athletes' technical abilities to apply force and therefore the impact of technique on force management could not be evaluated.

Differences in sprint performance and mechanical properties between sexes have been well established in the literature and are consistent with the results of this study. Men generally achieve faster sprint times due to greater levels of maximal velocity, greater levels of horizontal force and power, longer acceleration distances, longer step lengths and shorter CTs (8, 35). Higher P_{max} and F_0 are likely due to higher muscle mass and larger muscle fiber cross-sectional areas enabling a greater ability to produce force rapidly, Cheuvront et al. (7). Furthermore, these differences likely explain the significantly higher IMTP PF and relative PF observed in men in the current study. The significant differences in drop jump RSI can be largely attributed to the men attaining moderately higher JHs as differences in CT were considered small and non-significant.

No significant sex differences were found in any of the hop variables with CT, JH and RSI being near identical in men and women. This can be explained by the imposition of a set hopping frequency inducing an unintended limit on possible RSI scores. A frequency of 2.2

Hz constrains total hop time (contact and flight time) to a sum of 0.455 s, therefore the flight time, which is used to calculate JH, is limited based on the duration of the preceding CT. For example, a hop with a CT of 0.140 would only permit a flight time of 0.315 s, yielding a JH limitation to 0.122 m. Shorter CTs are possible in hopping compared to drop jumps since the imposed stretch loads, which are determined by the athlete's mass and the preceding hop height, are substantially lower. Consequently, the men and women were equally capable of tolerating the stretch loads and thus were equally limited in how high they could jump.

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

No relationship was found in the current study between IMTP PF, relative PF and drop jump RSI in men or women. Barr and Nolte (3) found a significant, moderate positive correlation between drop jump RSI (from 0.36 m) and 1RM front squat relative to body mass in female rugby players ($r = 0.44$). Additionally, Beattie et al. (4) found a significant moderate positive correlation between drop jump RSI (from 0.30 m) and PF measured during an IMTP ($r = 0.30$) but no significant correlation between relative PF and RSI, however, the aforementioned studies did not assess sprint athletes. Both the male and female athletes in the current study had higher RSI values than the participants in Beattie et al. (4) (Men: 2.06 ± 0.43, Women: 1.65 ± 0.35 versus: 1.37 ± 0.31) but considerably lower maximum strength scores (Men: 2642 ± 437 N, Women: 1913 ± 342 N versus 3578 ± 884 N). This highlights that high levels of maximum strength are not required to achieve high RSI scores. The higher RSI scores found in the present sprint athletes were most likely achieved as a result of several years of sprint and plyometric training.

PRACTICAL APPLICATIONS

For practitioners who wish to assess reactive strength in hopping, it is recommended that the test activity should not be constrained by the imposition of a set hopping frequency.

Practitioners and researchers are advised to use split times in addition to outcome measures for studies when investigating correlations because sprint performance is a multidimensional skill which requires a wide range of physical and technical demands. Furthermore, several methods of assessing reactive strength are needed that can better represent the demands present in the distinct phases of sprinting e.g. acceleration, maximum velocity and deceleration. Finally, it is concluded that greater levels of RSI, as assessed during a 0.3 m drop jump, do not necessarily require high levels of maximum strength. Training modalities that utilize movements with CTs below 0.250 s such as sprinting or plyometrics are advised to enhance fast SSC performance.

ACKNOWLEDGEMENTS

The authors have no conflict of interest to disclose and would like to thank Rosemary Daniel for her cooperation with testing and the Irish Research Council for financially supporting this research.

REFERENCES

1. Arampatzis A, Bruggemann GP, and Klapsing GM. Leg stiffness and mechanical energetic processes during jumping on a sprung surface. *Med Sci Sports Exerc* 33: 923-931, 2001.
2. Arsac LM and Locatelli E. Modeling the energetics of 100-m running by using speed curves of world champions. *J of Appl Physiol* 92: 1781-1788, 2002.
3. Barr MJ and Nolte VW. Which measure of drop jump performance best predicts sprinting speed? *J Strength Cond Res* 25: 1976-1982, 2011.
4. Beattie K, Carson BP, Lyons M, and Kenny IC. The Relationship between Maximal-Strength and Reactive-Strength. *Int J Sport Physiol 12*: 548-553, 2017.
5. Bolger R, Lyons M, Harrison AJ, and Kenny IC. Coaching sprinting: Expert coaches' perception of resistance-based training. Int J Sports Sci Coach 11: 746-754, 2016.
6. Chelly SM and Denis C. Leg power and hopping stiffness: relationship with sprint running performance. *Med Sci Sport Exer* 33: 326-333, 2001.
7. Cheuvront SN, Carter R, DeRuisseau KC, and Moffatt RJ. Running performance differences between men and women. *Sports Med* 35: 1017-1024, 2005.
8. Debaere S, Jonkers I, and Delecluse C. The contribution of step characteristics to sprint running performance in high-level male and female athletes. *J Strength Cond Res* 27: 116-124, 2013.
9. Delecluse C, Coppenolle HV, Willems E, Diels R, Goris M, Leemputte MV, and Vuylsteke M. Analysis of 100 meter sprint performance as a multi-dimensional skill. *J Hum Movement Stud* 28: 87, 1995.
10. Farley CT, Blickhan R, Saito J, and Taylor CR. Hopping frequency in humans: a test of how springs set stride frequency in bouncing gaits. *J of Appl Physiol* 71: 2127-2132, 1991.
11. Farley CT and Morgenroth DC. Leg stiffness primarily depends on ankle stiffness during human hopping. *J Biomech* 32: 267-273, 1999.

12. 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.
13. Harper D, Hobbs, S., Moore, J. The ten to five repeated jump test: A new test for evaluation of lower body reactive strength., in: *British Association of Sports and Exercises Sciences Student Conference*. Chester, 2011.
14. Healy R, Norris M, Kenny I, and Harrison AJ. A novel protocol to measure short sprint performance. *Procedia Engineer* 147: 706-711, 2016.
15. Hennessy L and Kilty J. Relationship of the stretch-shortening cycle to sprint performance in trained female athletes. *J Strength Cond Res* 15: 326-331, 2001.
16. Hobara H, Inoue K, Omuro K, Muraoka T, and Kanosue K. Determinant of leg stiffness during hopping is frequency-dependent. *Eur J of Appl Physiol* 111: 2195-2201, 2011.
17. Hopkins W, Marshall S, Batterham A, and Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc* 41: 3, 2009.
18. Hopkins WG. Measures of reliability in sports medicine and science. *Sports Med* 30: 1-15, 2000.
19. Kuitunen S, Komi PV, and Kyröläinen H. Knee and ankle joint stiffness in sprint running. *Med Sci Sport Exer* 34: 166-173, 2002.
20. Mackala K. Optimisation of performance through kinematic analysis of the different phases of the 100 metres. *New Stud athlete* 22: 7, 2007.
21. Maćkała K, Fostiak M, and Kowalski K. Selected determinants of acceleration in the 100m sprint. *J Hum Kinet* 45: 135-148, 2015.
22. Meckel Y, Atterbom H, Grodjinovsky A, Ben-Sira D, and Rotstein A. Physiological characteristics of female 100 metre sprinters of different performance levels. *J Sports Med Phys Fitness* 35: 169-175, 1995.
23. Morin J-B, Bourdin M, Edouard P, Peyrot N, Samozino P, and Lacour J-R. Mechanical determinants of 100-m sprint running performance. *Eur J of Appl Physiol* 112: 3921-3930, 2012.
24. Morin J-B and Samozino P. Interpreting power-force-velocity profiles for individualized and specific training. *Int J Sport Physiol* 11: 267-272, 2016.
25. Mrdakovic V, Ilic D, Vulovic R, Matic M, Jankovic N, and Filipovic N. Leg stiffness adjustment during hopping at different intensities and frequencies. *Acta Bioeng Biomech* 16: 69-76, 2014.
26. Nagahara R, Naito H, Miyashiro K, Morin J, and Zushi K. Traditional and ankle-specific vertical jumps as strength-power indicators for maximal sprint acceleration. *J Sports Med Phys Fitness* 54: 691-699, 2014.
27. Nicol C, Avela J, and Komi PV. The stretch-shortening cycle. *Sports Med* 36: 977-999, 2006.
28. Rabita G, Dorel S, Slawinski J, Sàez-de-Villarreal E, Couturier A, Samozino P, and Morin JB. Sprint mechanics in world-class athletes: a new insight into the limits of human locomotion. *Scand J Med Sci Spor* 25: 583-594, 2015.
29. Sale DG. Testing strength and power., in: *Physiological Testing of the High Performance Athlete*. J.D MacDougall, H.A. Wenger, and H.J. Green, ed. Champaign, IL: Human Kinetics, 1991.
30. Salo A and Bezodis I. Athletics: Which starting style is faster in sprint running standing or crouch start? *Sport Biomech* 3: 43-54, 2004.
31. Samozino P, Edouard P, Sangnier S, Brughelli M, Gimenez P, and Morin J-B. Force-velocity profile: imbalance determination and effect on lower limb ballistic performance. *Int J Sports Med* 35: 505-510, 2014.
32. Samozino P, Rabita G, Dorel S, Slawinski J, Peyrot N, Saez de Villarreal E, and Morin JB. A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. *Scand J Med Sci Spor* 26: 648-658, 2016.
33. Samozino P, Rejc E, Di Prampero PE, Belli A, and Morin J-B. Optimal Force–Velocity Profile in Ballistic. *Med Sci Sports Exerc* 44: 313-322, 2012.
34. Schmidtbleicher D. Training for power events, in: *Strength and Power in Sport*. PV Komi, ed. Boston, MA: Blackwell Scientific, 1992.

35. Slawinski J, Termoz N, Rabita G, Guilhem G, Dorel S, Morin JB, and Samozino P. How 100-m event analyses improve our understanding of world-class men's and women's sprint performance. *Scand J Med Sci Spor* 27:45-54, 2017.
36. Smirniotou A, Katsikas C, Paradisis G, Argeitaki P, Zacharogiannis E, and Tziortzis S. Strength-power parameters as predictors of sprinting performance. *J Sports Med Phys Fitness* 48: 447-454, 2008.
37. Smirniotou A, Katsikas C, Paradisis G, Argeitaki P, Zacharogiannis E, and Tziortzis S. Strength-power parameters as predictors of sprinting performance. *J Sports Med Phys Fitness* 48: 447-454, 2008.
38. Stone MH, Sands WA, Carlock J, Callan S, Dickie D, 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.
39. Thomas C, Comfort P, Chiang C-Y, and Jones PA. Relationship between isometric mid-thigh pull variables and sprint and change of direction performance in collegiate athletes. *J Trainol* 4: 6-10, 2015.
40. van Ingen Schenau GJ, Jacobs R, and de Koning JJ. Can cycle power predict sprint running performance? *Eur J of Appl Physiol Occup Physiol* 63: 255-260, 1991.
41. Wang R, Hoffman JR, Tanigawa S, Miramonti AA, La Monica MB, Beyer KS, Church DD, Fukuda DH, and Stout JR. Isometric Mid-Thigh Pull Correlates With Strength, Sprint, and Agility Performance in Collegiate Rugby Union Players. *J Strength Cond Res* 30: 3051-3056, 2016.
42. 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.
43. Weyand PG, Sandell RF, Prime DN, and Bundle MW. The biological limits to running speed are imposed from the ground up. *Journal of Appl Physiol* 108: 950-961, 2010.
44. 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 of Appl Physiol* 89: 1991-1999, 2000.
45. Young W. Laboratory strength assessment of athletes. *New Stud athlete* 10: 89-89, 1995.
46. Young W, McLean B, and Ardagna J. Relationship between strength qualities and sprinting performance. *J Sports Med Phys Fitness* 35: 13-19, 1995.