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Explosive force production during isometric squats correlates with athletic performance in rugby union players

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Abstract
This study investigated the association between explosive force production during isometric squats and athletic performance (sprint time and countermovement jump height). Sprint time (5 and 20 m) and jump height were recorded in 18 male elite-standard varsity rugby union players. Participants also completed a series of maximal- and explosive-isometric squats to measure maximal force and explosive force at 50-ms intervals up to 250 ms from force onset. Sprint performance was related to early phase ($\leq$100 ms) explosive force normalised to maximal force (5 m, $r = -0.63$, $P = 0.005$; and 20 m, $r = -0.54$, $P = 0.020$), but jump height was related to later phase ($>$100 ms) absolute explosive force ($0.51 < r < 0.61$; $0.006 < P < 0.035$). When participants were separated for 5-m sprint time ($<$ or $\geq$ 1s), the faster group had greater normalised explosive force in the first 150 ms of explosive-isometric squats (33–67%; $0.001 < P < 0.017$). The results suggest that explosive force production during isometric squats was associated with athletic performance. Specifically, sprint performance was most strongly related to the proportion of maximal force achieved in the initial phase of explosive-isometric squats, whilst jump height was most strongly related to absolute force in the later phase of the explosive-isometric squats.

Keywords: *rate of force development, explosive strength, isometric squats, countermovement jumps, sprinting*

Introduction

Human ability for explosive force production is considered important during sports activities where time to develop force is limited (such as sprinting, jumping and punching) (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002; de Ruiter, Kooistra, Paalman, & de Haan, 2004; Tillin, Jimenez-Reyes, Pain, & Folland, 2010). If this is the case, the assessment of explosive force production might provide practitioners with insight into the neuromuscular factors underpinning sports performance and facilitate the prescription of appropriate training. However, there is little evidence of an association between explosive force production and athletic performance. Explosive force production, measured as force at specific time points (or rate of force development) along the rising force-time curve, is typically assessed during: (i) single-joint exercises (Aagaard et al., 2002; Barry, Warman, & Carson, 2005; de Ruiter et al., 2004; Gruber et al., 2007; Tillin et al., 2010) as these provide more experimental control than multiple-joint exercises; and (ii) isometric actions as changes in muscle length/velocity influence force and confound the measurement of explosive force production (Tillin, Pain, & Folland, 2012). In contrast, sports activities are multiple-joint dynamic actions and thus provide distinct neural and mechanical conditions to those in which explosive force production is typically measured. It is therefore important to determine the association between multiple-joint explosive-isometric force production and athletic performance (specifically sprinting and jumping), if researchers and coaches are to infer practical implications from assessment of the former.

We recently found that explosive force production of the knee extensors was associated with athletic performance (Tillin et al., 2010), as a group of explosive athletes achieved $>$2 fold greater absolute force, and a higher proportion of their maximal force within the initial phase (first 50 ms) of explosive-isometric actions than untrained individuals. Nevertheless, it is unclear whether athletic performance/

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training influences the force-time curve of isometric multiple-joint activities in the same way as that observed in a single-joint situation. Studies have reported differences in multiple-joint isometric leg-press explosive force production among groups of distinct training backgrounds (Hakkinen & Keskinen, 1989; Kyrolainen & Komi, 1994; Viitasalo & Komi, 1978); however, when force was normalised to maximal force, to control for differences in strength, results were mixed (Hakkinen & Keskinen, 1989; Kyrolainen & Komi, 1994). Furthermore, these studies did not address technical issues that influence explosive-isometric force measurements.

A direct approach to understanding the relationship between athletic performance and explosive-isometric force production is to quantitatively relate these variables for a range of individuals. Two studies have assessed the relationship between explosive-isometric force production of the knee extensors and countermovement jump performance in small groups ($n \leq 11$), and whilst one reported a correlation between these parameters (de Ruiter, Van Leeuwen, Heijblom, Bobbert, & de Haan, 2006) the other did not (de Ruiter, Vermeulen, Toussaint, & de Haan, 2007). The discrepancy in these results might be because there are several muscle groups in addition to the knee extensors that contribute to jump performance. Explosive-isometric force production during various multiple-joint actions has been reported to be either strongly related to jump height (Marcora & Miller, 2000), or unrelated to jump height (isometric squats, (Nuzzo, McBride, Cormie, & McCaulley, 2008)). However, these studies considered explosive-isometric force production at only one time point during the rise of the force-time curve, and therefore may not have assessed the relevant force-time characteristics for jumping. To our knowledge, the relationship between sprint performance and explosive-isometric force production has not been examined.

Of the few studies that have measured explosive-isometric force production during multiple-joint situations (Hakkinen & Keskinen, 1989; Marcora & Miller, 2000; Nuzzo et al., 2008) none appear to have considered several technical issues that may have influenced their measurements of explosive force. Explosive-isometric actions should be performed from a steady baseline force to ensure that pre-tension was consistent and no countermovement occurred, as these factors can confound subsequent force measurements (de Ruiter et al., 2006; Grabiner, 1994; Kamimura, Yoshioka, Ito, & Kusakabe, 2009). A steady baseline force will also facilitate accurate identification of explosive force onset (Tillin et al., 2010). Finally, steps should be taken to minimise joint angle changes caused by soft tissue or measurement system compliance (Bojsen-Moller, Hansen, Aagaard, Kjaer, & Magnusson, 2003; Tsaopoulos, Baltzopoulos, Richards, & Maganaris, 2007), which are likely to confound force measurements.

The primary aim of this study was to investigate the relationship between athletic performance (specifically sprinting and jumping) and absolute and normalised force-time curves during explosive-isometric squats in a trained athletic group (elite varsity rugby union players). A secondary aim was to compare explosive-isometric force production in two groups with distinct athletic performance/training backgrounds (elite varsity rugby union players vs. controls). Care was taken to address technical issues associated with measuring explosive-isometric force production in a multiple-joint situation. We chose to investigate explosive-isometric performance in squats because this exercise is widely used for improving maximal and explosive strength of the lower body, and is kinematically similar to many functional sports activities (Schoenfeld, 2010), including sprinting and jumping.

Methods

Participants

Eighteen rugby union players (athletes; age, 20 ± 1 years; height, 183 ± 7 cm; and body mass, 92 ± 8 kg) and eight untrained individuals (controls; age, 22 ± 1 years; height, 186 ± 6 cm; and body mass, 83 ± 7 kg) volunteered to participate in this study. The athletes were varsity players competing in the English National League 2 level or higher, and were current (2010) champions of the British Universities and Sport Rugby Union trophy. The athletes were involved in regular strength and power training of the lower body (>3 times a week) in addition to regular matches (1 per week) and specific rugby training (≥ 3 times a week). The controls were low to moderately active (≤ 4 x aerobic activity a week), and were not involved in any strength and/or power training. All the participants were healthy, injury free and provided written informed consent prior to their involvement in this study, which was approved by the Loughborough University Ethical Advisory Committee.

Overview

Participants were instructed to refrain from any strenuous physical activity for 36 h and from alcohol consumption for 24 h, prior to visiting the laboratory. All measurements, which occurred between 8:00 and 11:00 am, were preceded by a warm-up of light aerobic exercise and dynamic stretches. The athletes visited the laboratory on a single occasion and completed a series of maximal and explosive lower-body activities (taking ~1 hr) including short (20 m) sprints, countermovement jumps, and maximal- and explosive-isometric squats (>5 min separated each activity). The athletes performed sprinting, jumping and squatting exercise on a regular basis and were familiar with good squat technique. The controls were unaccustomed to squat exercises. Therefore they had a practice session, to become accustomed with good isometric squat technique, followed by two identical measurement sessions (each separated by a week). The two measurement sessions of the controls were used to assess between-trials reliability and both sessions involved measurement of maximal- and explosive-isometric squat performance.

Measures

Sprints. A photocell timing system (Fusion Sport Smartspeed Queensland, Australia) assessed sprint times to the nearest 1/1000 of a second. After three sub-maximal sprints (at 50, 75 and 90% of maximum perceived effort, separated by 1 min), participants completed three maximal sprints (each separated by 3 min) in which they were instructed to run 26 m as quickly as possible, before decelerating. The sprint start was standardised as follows: participants assumed a split-stance crouch position (Cronin, Green, Levin, Brughelli, & Frost, 2007) with the toes of their preferred leg behind the start line. Once in position participants were instructed to lean back and hold their body weight over their back leg, where they were then given a '3-2-1-go' countdown. The first timing gate was positioned 1 metre from the start line, while the second and third timing gates were positioned at 5 and 20 m, respectively, from the first timing gate. The finish line was 5 m after the third timing gate to ensure that the participants did not slow down prematurely. The time taken for participants to run between the first and second (5 m) and first and third (20 m) timing gates was measured to the nearest millisecond via a hand held wireless module, and the best 5- and 20-m sprint time of the three sprints was recorded. Verbal encouragement and feedback on performance was given throughout.

Countermovement jumps. Countermovement jumps were completed on a 920 x 920 mm portable force plate (Kistler Quattro Jump, Winterthur, Switzerland) that sampled vertical ground reaction force at 500 Hz. After two practice attempts, participants performed three maximal jumps (each separated by $\geq$30 s). At the start of each jump participants were instructed to stand erect in the centre of the force plate with their shoulders pulled back, to ensure that their centre of mass was in a standardised position and at zero velocity. When ready, the participants were instructed to jump as high as possible using a countermovement to a self-selected depth and arm swing to optimise their performance. A jump was repeated if the participant did not land successfully in the centre of the force plate, or if they felt that their attempt was not maximal. Jump height (difference between the position of the centre of mass prior to commencing the jump and peak vertical displacement) was determined automatically using the double integration method by the force plate computer software (Quattro Jump, Type 2822A1-1, Version 1.0.9.2). For comparison with other studies, instantaneous power was determined as the product of force and velocity at any given time point. The greatest jump height, and peak power of the three attempts was recorded.

Isometric squats. Isometric squats were completed on a custom-designed, low-compliance squat rig (Figure 1), which consisted of a horizontal bar positioned above a force plate (Kistler 92868A, Winterthur, Switzerland). The bar height could be adjusted and fixed in 2.5-cm increments. Ground reaction forces recorded by the force plate were interfaced with an analogue-to-digital converter (CED micro 1401, CED, Cambridge, UK), sampled at 2000 Hz with a PC utilising Spike 2 software (CED, Cambridge, UK), and low-pass filtered at 160 Hz with a fourth-order zero-lag Butterworth filter. Zero force was defined as the participant's body weight. A computer monitor placed in front of the squat rig provided the participants with biofeedback. Participants stood (bare foot) on the force plate in a typical back-squat position with the horizontal bar touching their posterior deltoids and middle trapezius. The bar height was set at 75% of the participant's stature which, when the participant loaded the bar, gave ankle, knee, and hip angles of 83 ± 4, 118 ± 5, and 131 ± 8°, respectively. These joint angles were established by manually digitising (using Silicon Coach Software, Student version 6, New Zealand) sagittal plane photographs taken with a camera positioned 2.5 m from the participant (Figure 1). After a series of sub-maximal isometric squats, the participants completed three maximal squats (each separated by ~1 min) where they were instructed to push against the bar as hard as possible for 3–5 s. Throughout these squats (and the explosive squats; see below) the participants were allowed to place their fingers below the horizontal bar, but were instructed not to grip the bar. This ensured that the weight of the arms was not removed from the force

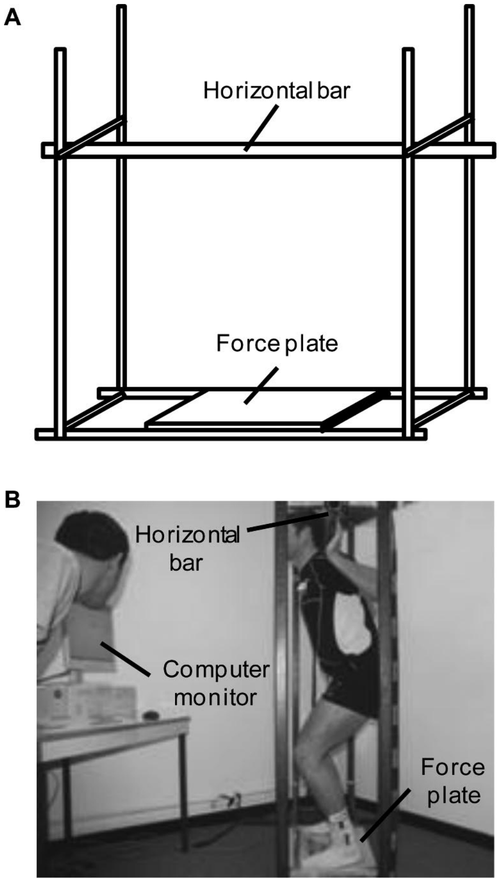

Figure 1. A schematic of the frontal view (A) and a photograph of the side view (B) of the isometric squat rig used to assess maximal- and explosive-leg strength. The participant positioned themselves on the force plate, in a back-squat position, with the horizontal bar touching the posterior deltoids and middle trapezius. The bar height was fixed at 75% of the participant's stature, which gave ankle, knee and hip angles of 83 ± 4, 118 ± 5, and 131 ± 8°, respectively, when the bar was loaded. A computer monitor in front of the participant provided biofeedback on performance.

plate during the effort. The greatest peak vertical ground reaction force of the three maximal squats was defined as maximal force, which was reported in absolute terms and relative to body mass by allometrically scaling with an appropriate power value (i.e., $N \cdot kg^{-0.66}$ (Folland, Mc Cauley, & Williams, 2008)).

The participants were given a 5-min recovery prior to performing the explosive squats. At the start of each explosive squat the participants assumed the squat position (as for the maximal squats) on the force plate and were instructed to apply a light steady baseline force (between 20 and 70 N) to the bar. To ensure that this was the case a computer monitor displayed baseline force in front of the participant, with the 20–70 N range highlighted. This baseline force, which subsequent analysis revealed was on average (mean ± *s*) 39 ± 6 N, ensured a good contact between the participant and bar, and removed the initial compliance caused by soft tissue compression. Once the baseline was steady the same investigator gave an auditory signal, upon which the participants were required to push against the bar as 'fast and hard' as possible for 1 s. Following one explosive squat the participants were instructed to reproduce a steady baseline force (which typically took 5–10 s) before attempting a second repetition. After 3–4 repetitions the participants were asked to step off the force plate and were given 30–60 s recovery before attempting another set of 3–4 explosive squats. Each participant completed 4–5 sets of explosive squats (>10 repetitions in total). The slope of the force-time curve (determined via a 1 ms epoch) was also displayed on the computer monitor in front of the participants to provide biofeedback on performance, and this was brought to the attention of participants after each explosive squat.

From off-line analyses, explosive-isometric squats were discarded if the baseline force changed by more than 10 N in the 200 ms before explosive force onset, to ensure that the explosive-isometric squats were performed from a steady baseline. Explosive-isometric squats were also discarded if baseline force was not between 1–3% of maximal force. This ensured that explosive force onset occurred at a similar point on the normalised force-time curve (normalised to maximal force; see below) in all trials and participants. Explosive force onset was defined as the last time that the slope of the force-time curve crossed zero. Of those explosive squats that met the criteria, the three with the greatest peak slope were analysed further. Specifically, force was recorded at 50-ms intervals from explosive force onset up to 250 ms, and normalised to absolute maximal force (i.e., expressed as a percentage of maximal force). Absolute and normalised force values were averaged across the three explosive squats analysed.

Statistical analysis

Group data are presented as mean ± standard deviation (*s*). The influence of group (athletes vs. controls) and time point (50, 100, 150, 200, and 250 ms) on explosive squat force (absolute and normalised) was analysed with a two-way mixed design factorial analysis of variance (ANOVA). Independent t-tests were then used to assess group differences in maximal force and explosive force at each time point from force onset. The meaningfulness of differences was assessed with Cohen's Effect Sizes (ES) and related criteria (Cohen, 1988). Pearson's product moment correlations and 95% confidence intervals assessed the strength of bivariate relationships between different dependent variables in the athletes. For group effects and bivariate relationships, statistical significance was set at $P < 0.05$. Between-trials reliability of the maximal- and explosive-isometric squat measurements was assessed by means of intra-class correlation coefficients (ICC) and coefficients of variation (CV; mean/*s*). An ICC was considered significant at $P < 0.05$. It was not possible to assess the reliability of sprint and jump performance in the current study. However, using similar methods past studies have reported good between-session reliability of measures of 5-m sprint time (ICC = 0.84; CV = 3.2%; (Gabbett, Kelly, & Sheppard, 2008)), 20-m sprint time (ICC = 0.96; CV = 1.3; (Gabbett et al., 2008)), and jump height (ICC = 0.99; (de Ruiter et al., 2007)), in team sport athletes. Statistical analysis was completed using SPSS version 17.

Results

Isometric squat performance of athletes vs. controls

The athletes had a greater maximal force than the controls (athletes, 2934 ± 339 vs. controls, 2142 ± 431 N; $P < 0.001$; ES = 1.53). Furthermore, although the athletes had greater body mass (athletes, 92.2 ± 8.5 vs. controls, 82.7 ± 6.8 kg; $P = 0.01$; ES = 1.05) they also had a greater maximal force scaled to body mass (athletes, 149 ± 19 vs. controls, 117 ± 24 $\mathrm{N} \cdot \mathrm{kg}^{-0.66}$; $P = 0.001$; ES = 1.27). Despite similar absolute force during the initial 100 ms of the explosive-isometric squats, athletes achieved a greater absolute explosive force at 200 (+29%; $P = 0.043$; ES = 0.90), and 250 ms (+28%; $P = 0.024$; ES = 0.99), and there was a tendency for a group difference at 150 ms (+24; $P = 0.086$; ES = 0.73) from force onset (Figure 2A). However, there were no differences between athletes and controls in explosive force normalised to maximal force at any of the measured time points from force onset (Figure 2B).

Relationships between isometric measurements and athletic performance

The athletes had a mean sprint time over 5 and 20 m of 1.003 ± 0.035 s (range, 0.943–1.051 s) and 2.994 ± 0.073 s (2.908–3.149 s), respectively. The mean jump height, peak power, and peak power relative to body mass were 59.7 ± 7.4 cm (range, 44.2–75.6 cm), 6134 ± 891 W (range, 4464–8241 W) and 66.6 ± 8.0 $\mathrm{W} \cdot \mathrm{kg}^{-1}$ (range, 49.8–84·7 $\mathrm{W.kg}^{-1}$), respectively. Five- and 20-m sprint times were related ($r = 0.55$; $P = 0.019$), whilst jump height was negatively related to sprint time over 20 m ($r = -0.62$; $P = 0.006$; Figure 3A), but not 5 m ($r = -0.19$; $P = 0.44$). Jump height was correlated with absolute maximal force ($r = 0.48$; $P = 0.046$), but not with maximal force scaled to body mass ($r = 0.42$; $P = 0.081$). There was no relationship between maximal force (absolute or scaled to body mass) and sprint performance (5 or 20 m; $-0.04 < r < 0.25$).

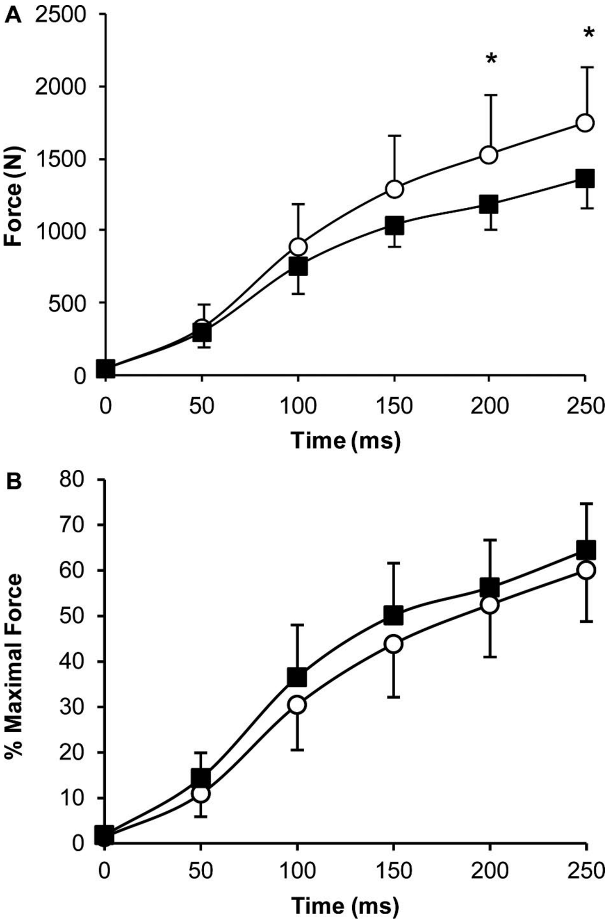

Figure 2. Absolute (A) and normalised (B) force during explosive-isometric squats in varsity rugby union players (open circles; $n = 18$) and untrained individuals (black squares; $n = 8$). Absolute force was vertical ground reaction force after body weight was subtracted, whilst normalised force was expressed as a percentage of maximal force. Data are group means ± *s*. A group effect is denoted by * ($P < 0.05$).

Sprint performance (5- and 20-m) was negatively correlated with absolute explosive force at only one time point (100 ms: $r = -0.5$; $0.034 < P < 0.037$; Table I and II). However, 5-m sprint time was negatively correlated with normalised force at 100 ms ($r = -0.63$; $P = 0.005$; Table I and Figure 3B), and tended to be negatively related to normalised force at 50 ($r = -0.42$; $P = 0.081$), and 150 ms ($r = -0.46$; $P = 0.057$; Table I). Sprint time over 20 m was negatively correlated with normalised force at 100 ms ($r = -0.54$; $P = 0.02$; Table II), and tended to be negatively correlated with normalised force at 150 ms ($r = -0.44$; $P = 0.066$; Table II).

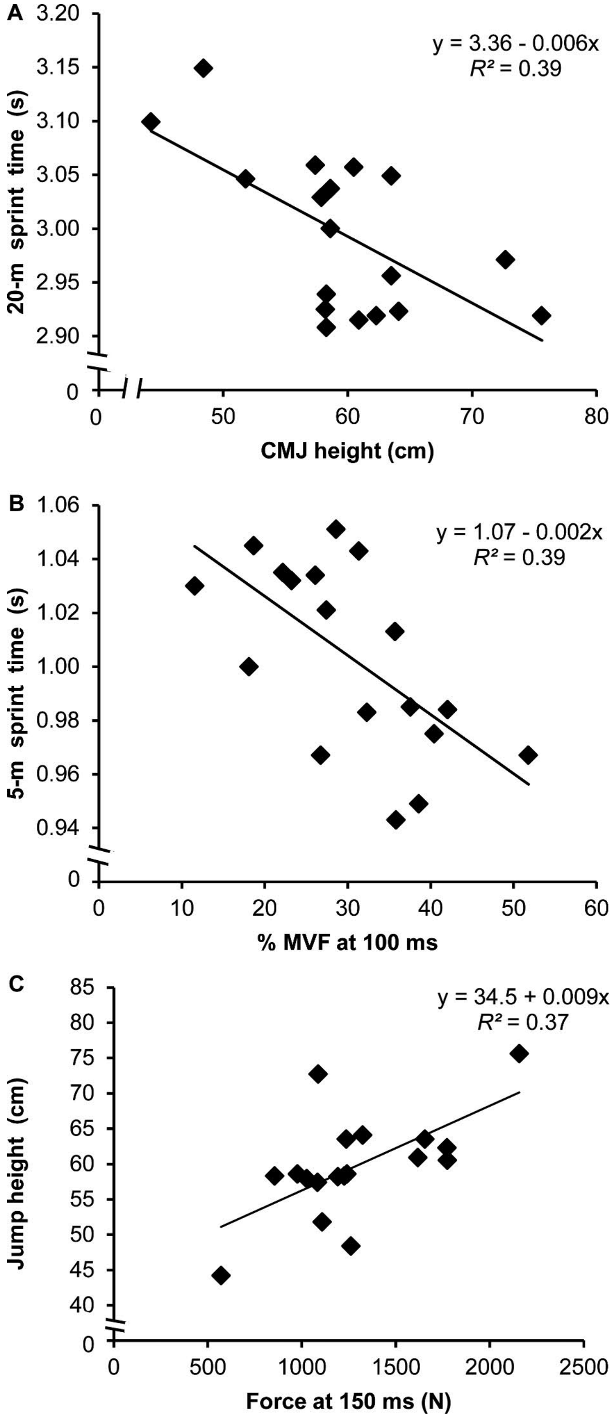

Figure 3. The relationship between countermovement jump height and 20-m sprint time (A); normalised explosive force after 100 ms during isometric squats and 5-m sprint time (B); and absolute explosive force after 150 ms during isometric squats and jump height (C). Data are for varsity rugby union players ($n = 18$). Absolute force is vertical ground reaction force after body weight is subtracted, whilst normalised force is expressed as a percentage of maximal force (after body weight is subtracted). The correlation coefficient in each figure was significant ($P < 0.01$).

Table I. Correlation coefficients and 95% confidence intervals of bivariate relationships between force (absolute and normalised) measured during explosive-isometric squats in varsity rugby union players ($n = 18$) and 5-m sprint time. Explosive force was normalised to absolute maximal force. A significant correlation is denoted by * ($P < 0.05$) or ** ($P < 0.01$).

Squat force at 50-ms intervals from force onset		Correlation coefficient	95% Confidence interval	
			Lower	Upper
Absolute	50	−0.32	−0.69	0.17
	100	−0.50*	−0.78	−0.04
	150	−0.30	−0.67	0.19
	200	−0.14	−0.58	0.37
	250	−0.03	−0.50	0.46
Normalised	50	−0.42	−0.74	0.06
	100	−0.63**	−0.85	−0.23
	150	−0.46	−0.76	0.01
	200	−0.36	−0.72	0.15
	250	−0.16	−0.60	0.35

Table II. Correlation coefficients and 95% confidence intervals of bivariate relationships between force (absolute and normalised) measured during explosive-isometric squats in varsity rugby union players ($n = 18$) and 20-m sprint time. Explosive force was normalised to absolute maximal force. A significant correlation is denoted by * ($P < 0.05$).

Squat force at 50-ms intervals from force onset		Correlation coefficient	95% Confidence interval	
			Lower	Upper
Absolute	50	−0.33	−0.69	0.17
	100	−0.50*	−0.79	−0.05
	150	−0.38	−0.72	0.11
	200	−0.18	−0.61	0.33
	250	−0.07	−0.53	0.43
Normalised	50	−0.36	−0.71	0.13
	100	−0.54*	−0.81	−0.10
	150	−0.44	−0.75	0.03
	200	−0.36	−0.72	0.15
	250	−0.15	−0.59	0.36

Jump height was significantly correlated with absolute force at 100 ($r = 0.51$; $P = 0.014$), 150 ($r = 0.61$; $P = 0.006$; Figure 3C), 200 ($r = 0.57$; $P = 0.02$) and 250 ms ($r = 0.51$; $P = 0.035$), and tended to be related to normalised force at 100, 150, and 200 ms ($0.33 < r < 0.43$; $0.052 < P < 0.089$; Table III).

Isometric squat performance of fast vs. slow sprinters

To explore the relationship between sprint performance and explosive force during the isometric squats further the athletes were separated into two groups: those that ran 5 m in <1 s (fast; $n = 10$) and those that ran 5 m in ≥ 1 s (slow; $n = 8$). These two groups had similar body mass (fast, 93.1 ± 9.4 vs. slow, 91.2 ± 7.7 kg; $P = 0.66$), absolute maximal force (fast, 2996 ± 223 vs. slow, 2856 ± 450 N; $P = 0.44$), and maximal force scaled to body mass (fast, 146 ± 26 vs. slow, 151 ± 12 N · kg$^{-0.66}$; $P = 0.75$). However, the fast group achieved a greater absolute explosive force at 50 (+62%; $P = 0.046$; ES = 0.41; Figure 4A) and 100 ms (+49%; $P = 0.008$; ES = 0.53; Figure 4A) from force onset and tended to achieve a greater absolute force at 150 ms (+27%; $P = 0.084$; ES = 0.36). Moreover, normalised force was also 33–67% greater at 50, 100, and 150 ms in the fast group ($0.001 < P < 0.017$; $0.48 < \text{ES} < 0.62$; Figure 4B), with a tendency for the same effect at 200 ms (+20%; $P = 0.085$; ES = 0.35).

Reliability of isometric squat force measurements

Measurements of explosive- and maximal-isometric squat strength in the controls had good between-trials reliability, demonstrated by the significant ICCs (Table IV). Maximal force and explosive force after 100 ms had the highest ICC values (0.96), with explosive force after 50 ms having the lowest ICC (0.74). During the explosive-isometric squats between-trials CV was largest at 50 ms from force onset (14.6%), but improved substantially at later time points in the squats (5.5–7.4%). The lowest CV was for maximal force (4.0%; Table IV).

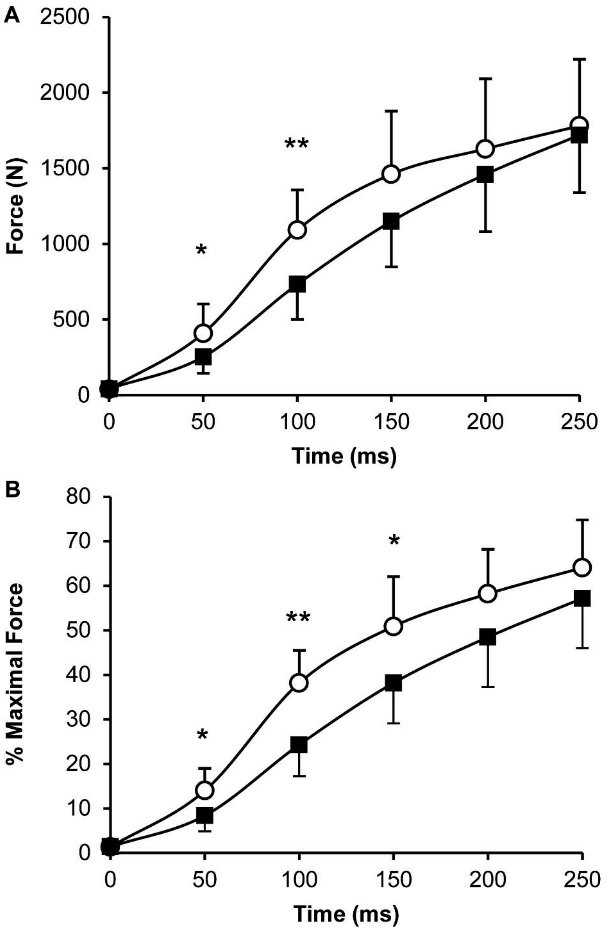

Figure 4. Absolute (A) and normalised (B) force during explosive-isometric squats in varsity rugby union players separated into two groups depending on their 5-m sprint time; <1 s (open circles; $n = 8$) or ≥1 s (black squares; $n = 10$). Absolute force is vertical ground reaction force after body weight is subtracted, whilst normalised force is expressed as a percentage of maximal force (after body weight is subtracted). Data are means ± *s*. A group effect is denoted by * ($P < 0.05$) or ** ($P < 0.01$).

Discussion

While explosive-isometric force production is considered to be an important indicator of performance in maximal-intensity-type athletic activities (Aagaard et al., 2002; de Ruiter et al., 2004; Tillin et al., 2010), there is limited evidence to support this theory. The current study found clear relationships between explosive force during isometric squats and both sprint and jump performance, confirming the association between explosive-isometric and athletic tasks. Furthermore, when the athletes were separated into those that could sprint 5 m in <1 s and those

Table III. Correlation coefficients and 95% confidence intervals of bivariate relationships between force (absolute and normalised) measured during explosive-isometric squats in varsity rugby union players ($n = 18$) and countermovement jump height. Explosive force was normalised to absolute maximal force. A significant correlation is denoted by * ($P < 0.05$) or ** ($P < 0.01$).

Squat force at 50-ms intervals from force onset		Correlation coefficient	95% Confidence interval	
			Lower	Upper
Absolute	50	0.22	−0.21	0.67
	100	0.51*	0.14	0.82
	150	0.61**	0.21	0.84
	200	0.57*	0.11	0.82
	250	0.51*	0.04	0.80
Normalised	50	0.11	−0.31	0.60
	100	0.33	−0.07	0.74
	150	0.43	−0.002	0.77
	200	0.38	−0.06	0.76
	250	0.26	−0.18	0.70

Table IV. The intra-class correlation coefficients (ICC) and average between-trials coefficient of variation (CV%) for repeated measures of maximal force and explosive force recorded at 50-ms intervals from force onset during explosive-isometric squats, in untrained individuals. A significant ICC is denoted by * ($P < 0.05$), ** ($P < 0.01$), or *** ($P < 0.001$).

	CV%	ICC
Maximal force	4.0	0.96***
Explosive force at 50 ms	14.6	0.74*
Explosive force at 100 ms	7.4	0.96***
Explosive force at 150 ms	5.3	0.88**
Explosive force at 200 ms	7.9	0.78*
Explosive force at 250 ms	6.3	0.88*

that couldn't, the faster group displayed greater normalised explosive force in the initial phase of the squat (first 50–150 ms). When comparing the athletes and controls in this study, differences in absolute explosive force production could be attributable to strength discrepancies, as these groups displayed similar normalised force-time curves (normalised to maximal force).

The between-trials CV of absolute force measured during the isometric squats (maximal force, 4%; and explosive force at 50 ms, 15%; 100ms, 7%; and 150 ms, 5%) was similar to that previously observed in an isolated muscle group (the knee extensors; maximal force, 2.3–3%; and explosive force at 50 ms, 13%; 100 ms, 5%; and 150 ms, 5% (Tillin, Pain, & Folland, 2011)). Single-joint studies have shown that initial explosive-isometric force production is strongly influenced by agonist activation (de Ruiter et al., 2004; de Ruiter et al., 2006), and therefore the high CV that occurs in agonist activation (12.2% (Tillin et al., 2010)) may explain the variability in explosive force at 50 ms. Nevertheless, the significant ICCs of explosive force production at all time points during isometric squatting indicates a reliable method of assessing the force-time curve in a multiple joint activity, where care was taken to ensure a stable baseline force; a consistent explosive force onset across trials and participants; and minimal system compliance during the explosive efforts.

The athletes produced greater explosive-squat force than the controls after the initial 150 ms from explosive force onset. However, this difference appeared to be due to the athletes being 37% stronger than the controls, as normalised explosive-squat force was comparable for the two groups at all measured time points. The influence of maximal force on rate of force development is thought to increase with time from force onset (Andersen & Aagaard, 2006; Tillin et al., 2010), which may explain why group differences in absolute force only became evident at later time points during the explosive squats. In contrast to the current results, we have previously reported that explosive athletes have a greater normalised explosive force production in the initial 50 ms of explosive-isometric knee extensions (Tillin et al., 2010). However, the athletes in our earlier study were national/international level sprinters and jumpers, and thus had a demonstrated ability for explosive athletic performance. In contrast, the athletes in the current investigation were rugby union players who might be expected to have varying levels of explosive athletic ability, depending on the physical demands of their position. For example, forwards spend large periods of the game performing high force, slow speed activities (e.g., scrummaging, rucking and mauling), and less time performing explosive activities, such as sprinting (Roberts, Trewartha, Higgitt, El-Abd, & Stokes, 2008).

The sprint times recorded by the athletes in the current study (5 m, 1.00 ± 0.04 s; 20 m, 2.99 ± 0.07 s) were slightly slower than those previously observed in elite sprinters (5 m, 0.97 ± 0.09 s; (Dowson, Nevill, Lakomy, Nevill, & Hazeldine, 1998)), but they were comparable to British international and/or elite national rugby union players (5 m, 1.00 ± 0.06 s; (Dowson et al., 1998)), and Norwegian elite national soccer players (20 m, 3.0 ± 0.3 s; (Wisloff, Castagna, Helgerud, Jones, & Hoff, 2004)), and better than Australian premier rugby league players (20 m, 3.25 ± 0.16 s; (Gabbett et al., 2008)). Furthermore, mean countermovement jump height in the current study (60 ± 7 cm) was comparable to that measured in Netherlands premier league volleyball players (61 ± 6 cm; (de Ruiter et al., 2007)) and greater than that previously observed in untrained (recreationally active) individuals (52 ± 9 cm; (Harman, Rosenstein, Frykman, & Rosenstein, 1990)). Although some of the differences between studies may be partly due to methodology discrepancies, the above comparisons suggest that the athletes in the current study had comparable explosive athletic ability to team-sport athletes competing at a high level. The observed relationship between jump height and 20-m sprint time was consistent with earlier studies that have also reported a commonality in performance in these two activities (Cronin & Hansen, 2005; Peterson, Alvar, & Rhea, 2006). However, it is unclear why jump height was not related to 5-m sprint time. It is possible that technical aspects contributing to jump performance are more relevant to sprinting over longer distances, although this requires further investigation. Furthermore, sprint time over 20 m is known to be more reliable than over 5 m (Gabbett et al., 2008), which would improve the probability of detecting an underlying relationship.

When the athletes were separated by 5-m sprint performance, those that ran 5 m in <1 s achieved a greater proportion of their maximal force in the initial phase (first 50–150 ms) of explosive-isometric squats, than those that ran 5 m in ≥ 1 s. However, normalised explosive force during the later phase of the squats (200 and 250 ms) was similar for the two groups. These results show that the ability to explosively utilise the available maximal force during the early phase, but not during the later phase, of isometric squats was different for fast and slow sprinters, and indicates that normalised explosive strength in this early phase may be an important determinant of sprint performance. This is consistent with our earlier observation for an isolated muscle group (Tillin et al., 2010); where sprinters and jumpers displayed greater normalised explosive force production in the early, but not the late phase, of explosive-isometric knee extensions compared to untrained individuals. The association of normalised explosive strength during squatting with sprint performance was supported by the significant inverse relationships between sprint performance (5- and 20-m) and normalised explosive-squat force at 100 ms. The reason for greater initial normalised explosive-squat force in faster runners may be due to more effective agonist activation in the short time period available in both of these situations (Tillin et al., 2010). In contrast, the similar normalised explosive force at later time points for fast and slow runners is consistent with the finding of no relationship between maximal force and sprint performance, and the increased influence of maximal force on later phase explosive strength (Andersen & Aagaard, 2006; Tillin et al., 2010).

Whilst normalised explosive-isometric force during the early phase (100 ms) of the squats was most strongly related to sprint time (5 m, $r^2 = 0.40$; 20 m $r^2 = 0.29$), absolute explosive-isometric force after 100 ms was most strongly related to jump height (150 ms, $r^2 = 0.37$). It seems likely that this discrepancy is associated with the time to develop force in these two situations. Foot contact time during the acceleration phase of sprinting is <300 ms, and ~ 100 ms at top speed (Weyand, Sternlight, Bellizzi, & Wright, 2000). It is unlikely that maximal force will be achieved in this time (Aagaard et al., 2002; Thorstensson, Karlsson, Viitasalo, Luhtanen, & Komi, 1976), and therefore the proportion of maximal force that can be achieved in the time available would be a logical predictor of sprint performance. In contrast, the length of time for force production during a countermovement jump (i.e., from the start of the countermovement to take-off) ranged from 700–1100 ms in the current study. This time is sufficient to achieve high absolute levels of force and potentially maximal force. Hence jump height is likely to be more reliant on the overall capacity for absolute force production. This would explain the relationship between jump height and explosive absolute force at all measured time points after 50 ms, and between jump height and maximal force.

Although maximal force (absolute and scaled to body mass) was related to jump height ($0.42 < r < 0.48$), previous studies have reported a stronger association between these variables ($0.78 < r < 0.86$; (Peterson et al., 2006; Wisloff et al., 2004)). Furthermore, we found no relationship between maximal force (absolute or scaled to body mass) and sprint performance, despite earlier studies reporting a commonality between leg strength and sprint performance (Alexander, 1989; Dowson et al., 1998; Peterson et al., 2006; Wisloff et al., 2004). However, these earlier studies measured leg strength during dynamic actions (compared to isometric actions in the current study), and whilst measures of dynamic and isometric strength are considered to be related (Blazevich, Gill, & Newton, 2002; Haff, Stone, O'Bryant, Dinan, & Johnson, 1997), dynamic strength is likely to be more specific to functional athletic performance (Baker, Wilson, & Carlyon, 1994). Furthermore, the participants in the present study were fairly homogenous for age, gender, and athletic/training background. This may have minimised the range of scores in their performance parameters and reduced the chance of observing significant relationships between the dependent variables. Two other investigations have also reported a poor relationship between leg strength (absolute or relative to body mass) and both jump height and sprint performance in a fairly homogenous group of rugby players (Baker & Nance, 1999; Cronin & Hansen, 2005). Clearly further work is required to understand the relationship between strength and athletic performance.

Although explosive-isometric and dynamic activities provide distinct neural and mechanical conditions, the results of this study confirm an association between dynamic athletic performance and explosive-isometric force production that was previously only assumed. Moreover, the nature of this association is dependent on the force-time characteristics of the athletic activity. This has important implications for both designing training programmes and monitoring explosive muscle function. For example, training for an activity where time to develop force is similar to that of sprinting, should predominantly involve exercises aimed at improving the muscles ability to utilise the available maximal force as quickly as possible (e.g., ballistic resistance training). In contrast, training for an activity where time to develop force is similar to or longer than countermovement jumps, should predominantly involve exercises aimed at improving maximal force (e.g., heavy resistance training). Finally, assessing an athlete's explosive force over different time periods from force onset may provide a useful method of monitoring their abilities in different aspects of explosive athletic performance.

In conclusion, this study presents a reliable method of assessing explosive-isometric squat performance over different time periods from force onset in a multiple-joint situation. Explosive force production during isometric squatting was associated with explosive athletic performance; specifically normalised explosive force during the early phase (100 ms) of the squats was most strongly associated with sprint time, whereas absolute explosive force after 100 ms was most strongly related to jump height.

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