# TRANSFER EFFECT OF STRENGTH AND POWER TRAINING TO THE SPRINTING KINEMATICS OF INTERNATIONAL RUGBY PLAYERS

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## ABSTRACT

Barr, MJ, Sheppard, JM, Agar-Newman, DJ, and Newton, RU. Transfer effect of strength and power training to the sprinting kinematics of international rugby players. *J Strength Cond Res* 28(9): 2585–2596, 2014—Increasing lower-body strength is often considered to be important for improving the sprinting speed of rugby players. This concept was examined in a group ($n = 40$) of international rugby players in a 2-part study. The players were tested for body mass (BM), 1 repetition maximum power clean (PC), and front squat, as well as triple broad jump and broad jump. In addition, speed over 40 m was tested, with timing gates recording the 0- to 10-m and 30- to 40-m sections to assess acceleration and maximal velocity. Two video cameras recorded the 2 splits for later analysis of sprinting kinematics. The players were divided into a fast group ($n = 20$) and a slow group ($n = 20$) for both acceleration and maximal velocity. In the second part of the study, a group ($n = 15$) of players were tracked over a 1-year period to determine how changes in strength corresponded with changes in sprinting kinematics. The fast groups for both acceleration and maximal velocity showed greater levels of strength ($d = 0.5$–$1.8$), lower ground contact times ($d = 0.8$–$2.1$), and longer stride lengths ($d = 0.5$–$1.3$). There was a moderate improvement over 1 year in PC/BM ($0.08\ \mathrm{kg \cdot kg^{-1}}$, $p = 0.008$, $d = 0.6$), and this had a strong relationship with the change in maximal velocity stride length ($r = 0.70$). Acceleration stride length also had a large improvement over 1 year ($0.09$ m, $p = 0.003$, $d = 0.81$). Although increasing lower-body strength is likely important for increasing sprinting speed of players with low training backgrounds, it may not have the same effect with highly trained players.

**KEY WORDS** exercise selection, ground contact time, maximal sprinting velocity

## INTRODUCTION

Speed is commonly considered to be a highly valuable ability in rugby union (11), and the selection of different training methods to improve sprinting speed is an important part of training rugby players (12). Improving leg strength relative to body mass (BM) has been suggested as a way of positively improving the sprinting speed of athletes (9,12). A rationale for this is that decreasing ground contact time, particularly at maximal velocity, is considered the most important kinematic change for improving sprinting speed (39). An increase in force production must occur if a decrease in ground contact time is to happen (39). The vertical velocity of the center of gravity, which has been reported (26) to change from $-0.5$ to $0.5\ \mathrm{m \cdot s^{-1}}$ during the maximal velocity sprinting stride, requires high force production. Decreasing ground contact time and maintaining this change in vertical velocity would require a further increase in the average force production (26,39). For example, a 100-kg rugby player who shortens his ground contact time from 0.12 to 0.10 seconds must hypothetically increase the average vertical force during his stance phase from 1,814 N (185 kg) to 1,981 N (202 kg) if he is to raise his center of gravity $0.5\ \mathrm{m \cdot s^{-1}}$ during each stride (26). If this player had a typical maximal velocity stride length of 2.2 m and a flight time of 0.12 seconds, and maintained these with the above reduction in ground contact time, he would hypothetically increase his maximal velocity from 9.2 to $10\ \mathrm{m \cdot s^{-1}}$. A change of this magnitude would be an improvement in an international or professional rugby player's speed from average to exceptional (11,19). Selecting appropriate strength and power exercises that help to increase the ability to develop force relative to BM and decrease ground contact time have been suggested to be a highly important aspect of training program design for improving sprinting speed (26,37,39).

Ground contact times are much longer during initial and mid-acceleration phases when compared with maximal velocity (5). This indicates that they could be considered different speed qualities (5). The differences in ground contact times between speed qualities may also mean that different strength qualities (maximal strength, explosive strength, reactive strength, etc.) may be more important at

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*28(9)/2585–2596*

*Journal of Strength and Conditioning Research*

**Table 1.** Typical strength and speed exercises used during training.

| Speed exercises | Strength, power, and plyometric exercises |
|---|---|
| Flat sprints (10–60 m) | Squats (back, front, split) |
| 3° Uphill sprints (10–20 m) | Presses (bench, military, push, incline) |
| Sled sprints (5–15 m) | Upper body pulls (chin-up, bent over row, pull-up) |
| 3° Downhill sprints (20–40 m) | Cleans (squat, power, split, pulls, from floor, from hang, from blocks) |
| Change of direction drills | Snatches (power, split, pulls, from floor, from hang, from blocks) |
| | Jerks (power, split) |
| | Weighted jumps (barbell, kettlebell, unilateral, bilateral) |
| | Horizontal jumps (broad, mulitple broad, single leg bounds) |
| | Eccentric load jumps (drop jumps, eccentric release jumps) |
| | Assisted jumps |
| | Back exercises (good morning, back extension) |
| Training volume | Training volume |
| 100–350 m per session total | 4–6 exercises per session |
| Volume | 5–8 sets per exercise |
| | 1–8 repetetions per set |
| | Sessions typically concluded with abdominal exercises and small muscle group injury prevention type exercises for ankles, necks, rotator cuffs, etc |

different phases of a sprint, based on the time available to develop force (43). Previous studies that have examined speed and strength quality relationships have found strong correlations between sprinting speed and maximal strength, explosive strength and reactive strength (3,4,6,8,17,21,28,31,36,41). Eight of these studies timed an acceleration component (~10 m), 7 timed a longer sprint distance (~40 m), and only 3 measured a maximal sprinting velocity. Only one of these studies measured stride length and stride rate, with no study has examining the relationship between ground contact time and lower-body strength.

Training studies investigating programs, which incorporate maximal strength or explosive strength training exercises

**Table 2.** Differences between the fast acceleration group and the slow acceleration group for anthropometric measures, sprinting kinematics, and strength and power exercises.

| | Fast group ($n = 20$) | Slow group ($n = 20$) | $p$ | Effect size (d) | Magnitude |
|---|---|---|---|---|---|
| Anthropometric | | | | | |
| Height (m) | 1.84 ± 0.07 | 1.84 ± 0.06 | 0.88 | 0.04 | Trivial |
| Mass (kg) | 93.2 ± 8.9 | 103.8 ± 12.4 | 0.004 | 1.2 | Large |
| Acceleration sprinting kinematics | | | | | |
| Initial sprinting velocity ($m \cdot s^{-1}$) | 5.88 ± 0.13 | 5.48 ± 0.17 | <0.0001 | 3.4 | Very large |
| Stride rates (strides per second) | 4.27 ± 0.23 | 4.16 ± 0.23 | 0.15 | 0.5 | Small |
| Stride length (m) | 1.25 ± 0.08 | 1.21 ± 0.10 | 0.16 | 0.5 | Small |
| Relative stride length ($m \cdot m^{-1}$) | 0.68 ± 0.06 | 0.66 ± 0.06 | 0.23 | 0.4 | Small |
| Ground contact time (s) | 0.16 ± 0.01 | 0.17 ± 0.02 | 0.0345 | 0.8 | Moderate |
| Flight time (s) | 0.07 ± 0.01 | 0.07 ± 0.01 | 0.2798 | 0.4 | Small |
| Strength and power | | | | | |
| Front squat (kg) | 138 ± 15 | 138 ± 15 | 0.97 | 0.01 | Trivial |
| Front squat/body mass ($kg \cdot kg^{-1}$) | 1.5 ± 0.21 | 1.33 ± 0.15 | 0.005 | 0.8 | Moderate |
| Power clean (kg) | 121 ± 11 | 117 ± 9 | 0.24 | 0.3 | Small |
| Power clean/body mass ($kg \cdot kg^{-1}$) | 1.30 ± 0.13 | 1.14 ± 0.13 | 0.0004 | 1.2 | Large |
| Broad jump (m) | 2.68 ± 0.12 | 2.46 ± 0.28 | 0.0007 | 1.7 | Large |
| Triple broad jump (m) | 8.44 ± 0.46 | 7.54 ± 0.62 | 0.0001 | 1.7 | Large |

**TABLE 3.** Differences between the fast maximal velocity group and the slow maximal velocity group for anthropometric measures, sprinting kinematics, and strength and power exercises.

| | Fast group ($n = 20$) | Slow group ($n = 20$) | $p$ | Effect size (d) | Magnitude |
|---|---|---|---|---|---|
| Anthropometric | | | | | |
| Height (m) | 1.82 ± 0.07 | 1.86 ± 0.06 | 0.12 | 0.5 | Small |
| Mass (kg) | 92.2 ± 9.2 | 104.8 ± 11.0 | 0.0004 | 1.4 | Large |
| Maximal velocity sprinting kinematics | | | | | |
| Maximal sprinting velocity ($m \cdot s^{-1}$) | 9.29 ± 0.29 | 8.36 ± 0.44 | <0.0001 | 3.2 | Very large |
| Stride rates (strides/s) | 4.55 ± 0.26 | 4.21 ± 0.29 | 0.0005 | 1.3 | Large |
| Stride length (m) | 2.06 ± 0.09 | 1.99 ± 0.14 | 0.06 | 0.8 | Moderate |
| Relative stride length ($m \cdot m^{-1}$) | 1.13 ± 0.05 | 1.07 ± 0.06 | 0.0007 | 1.3 | Large |
| Ground contact time (s) | 0.10 ± 0.01 | 0.12 ± 0.02 | 0.0001 | 2.1 | Very large |
| Flight time (s) | 0.12 ± 0.01 | 0.12 ± 0.01 | 0.76 | 0.1 | Trivial |
| Strength and power | | | | | |
| Front squat (kg) | 134 ± 15 | 141 ± 13 | 0.14 | 0.4 | Small |
| Front squat/body mass ($kg \cdot kg^{-1}$) | 1.46 ± 0.2 | 1.36 ± 0.19 | 0.11 | 0.5 | Small |
| Power clean (kg) | 119 ± 12 | 118 ± 8 | 0.69 | 0.1 | Trivial |
| Power clean/body mass ($kg \cdot kg^{-1}$) | 1.30 ± 0.13 | 1.14 ± 0.13 | 0.0003 | 1.2 | Large |
| Broad jump (m) | 2.69 ± 0.13 | 2.45 ± 0.20 | 0.0001 | 1.8 | Large |
| Triple broad jump (m) | 8.44 ± 0.53 | 7.66 ± 0.58 | <0.0001 | 1.5 | Large |

have found improvements in the sprinting speeds of athletes (10,15,18,27). Rimmer and Sleivert (33) noted an improvement in sprinting speed, with a corresponding decrease in ground contact time, after a program of plyometric training. There is little other research, however, examining the relationships between changes in strength and sprinting kinematics. This study aimed to develop a greater understanding of the relationship between changes in strength qualities and changes in the sprinting kinematics of elite rugby players. It is hypothesized that stronger and more powerful players will display higher velocities, higher stride rates, longer stride lengths, and lower ground contact times than their weaker peers. It is expected that the relationship between strength qualities and sprinting kinematics would be different between acceleration and maximal velocity phases and between fast and slow groups. Lastly, it is hypothesized that long-term changes in strength qualities would correspond with improvements in sprinting kinematics as predicted by cross-sectional data.

## METHODS

### Experimental Approach to the Problem

To understand how the development of lower-body strength qualities affects sprinting speed, the study was divided into 2 parts. The first part consisted of a causal-comparative cross-sectional design, whereas the second part of the study was a longitudinal quasi-experimental design. The first part of the study consisted of examining the relationship between sprinting kinematics and lower-body strength qualities in a group of rugby players ($n = 40$). The group was twice divided into fast ($n = 20$) and slow ($n = 20$) groups based on sprinting speed for both the 0- to 10-m and 30- to 40-m segments. The second part of the study consisted of tracking a group of elite ($n = 15$) rugby players over a year period to determine if increasing leg strength qualities were associated with an improvement in sprinting kinematics.

### Subjects

In part 1, a group of players ($n = 40$) underwent a series of assessments to characterize their sprinting ability and lower limb muscle function characteristics. The players (height = 1.84 ± 0.07 m, mass = 98.5 ± 11.9 kg, and 22.2 ± 3.0 years) who participated in the study were a mix of 21 senior international rugby players, 14 under-20 national team players, and 5 uncapped players belonging to a senior national team academy. The national team that all of the players were affiliated with is typically ranked 11th–15th place on the International Rugby Board world rankings. All of the players in the study, before the testing, had a minimum of 50 strength training and 20 sprint training sessions that were supervised by a strength and conditioning coach who gave them specific technical feedback. In part 2, a smaller group of players ($n = 15$) were measured at the beginning and end of a 1-year period using the same methods as part 1. All of the players in part 2 (1.84 ± 0.05 m, 100.6 ± 11.2 kg, and 24.1 ± 3.4 years) played either senior 15s or 7s national team rugby during the experimental period and had a history of at least 3 years of supervised speed and strength training. All participants gave informed written consent to take part in the study that had institutional review board approval.

**Table 4.** Pearson's correlations between acceleration sprinting kinematics, anthropometric measures and strength and power measures.*

| | | Height | Mass | Front squat/body mass | Power clean/body mass | Broad jump | Triple broad jump |
|---|---|---|---|---|---|---|---|
| Initial sprinting velocity | Group | 0.14 | −0.61 | 0.50 | 0.70 | 0.75 | 0.75 |
| | Slow | 0.13 | −0.54 | 0.21 | 0.68 | 0.73 | 0.72 |
| | Fast | 0.18 | −0.52 | 0.52 | 0.67 | 0.66 | 0.69 |
| Stride rate | Group | −0.25 | −0.42 | 0.50 | 0.51 | 0.32 | 0.36 |
| | Slow | −0.35 | −0.56 | 0.63 | 0.50 | 0.16 | 0.12 |
| | Fast | −0.20 | −0.12 | 0.34 | 0.43 | 0.40 | 0.51 |
| Stride length | Group | −0.07 | −0.32 | 0.20 | 0.29 | 0.44 | 0.43 |
| | Slow | 0.14 | −0.23 | 0.06 | 0.35 | 0.55 | 0.60 |
| | Fast | −0.07 | −0.35 | 0.27 | 0.36 | 0.49 | 0.47 |
| Relative stride length | Group | −0.51 | −0.56 | 0.40 | 0.44 | 0.36 | 0.38 |
| | Slow | −0.28 | −0.49 | 0.16 | 0.50 | 0.48 | 0.52 |
| | Fast | −0.72 | −0.61 | 0.51 | 0.32 | 0.07 | 0.10 |
| Ground contact time | Group | 0.45 | 0.67 | −0.50 | −0.62 | −0.44 | −0.43 |
| | Slow | 0.22 | 0.71 | −0.47 | −0.61 | −0.30 | −0.20 |
| | Fast | 0.34 | 0.64 | −0.46 | −0.56 | −0.37 | −0.36 |
| Flight time | Group | −0.19 | −0.36 | 0.09 | 0.22 | 0.19 | 0.15 |
| | Slow | 0.05 | −0.29 | −0.07 | 0.21 | 0.17 | 0.10 |
| | Fast | −0.10 | −0.39 | 0.12 | 0.25 | 0.19 | 0.14 |

*The top number is the correlation for the whole group ($n = 40$), the middle number is the acceleration-slow group ($n = 20$), and the bottom number is the acceleration-fast group ($n = 20$).

### Speed Assessment

Each of the players performed four 40-m sprints on artificial field using a Brower system (Brower, Draper, UT, USA) with timing gates placed on 1-m high tripods at 0, 10, 30, and 40 m. The players began each sprint with their front foot beside a cone 0.75 m behind the first gate. The 0- to 10-m split was used to assess acceleration ability, and the 30- to 40-m split was used to assess maximal velocity sprinting ability (5). Before the testing period, the participants undertook a 25-minute warm-up that included light running, dynamic stretches, and three 40-m sprints that progressively increased in intensity from 60% of maximal volitional effort to 95% of maximal effort. After warm-up, the participants were given a 4-minute break before they performed their first 40-m sprint and 4–5 minutes of passive rest after each subsequent sprint. The fastest 0- to 10-m split, the fastest 30- to 40-m split, and all corresponding kinematics from those trials were kept for analysis. The 0- to 10-m and 30- to 40-m splits were converted into velocities by dividing the 10-m distance by the time taken to complete it. The velocity from the 0- to 10-m split was considered to be initial sprinting velocity (ISV), and the 30- to 40-m split was considered to be maximal sprinting velocity (MSV).

To characterize sprinting kinematics, each of the sprints was filmed using 2 Nikon J1 video cameras recording at 400 frames per second. Calibration markers were placed 0.5 m to either side of the run at 0, 6, 30, and 36 m. The first camera recorded the 0- to 6-m section and the second camera recorded the 30- to 36-m section. To assess the sprinting kinematics of each player, stride rate (SR), stride length (SL), relative stride length (RSL), ground contact time (GCT), and flight time (FT) were calculated (26) with the aid of computer software (Kinovea). A stride was considered to be the time from touchdown from one leg to the last instant before touchdown of the other leg (26). Stride length was determined by measuring the distance between successive toe-off positions in each stride, with the most anterior part of the foot at toe off used as a marker for measuring stride length. Relative stride length was calculated by dividing stride length by the height of the athlete. Ground contact times were calculated by counting the number of frames (0.0025 seconds per frames) between touchdown and toe off. Flight time was determined by counting the number of frames between toe off and touchdown. Stride rate was determined by dividing one stride by the time taken to complete it (1/ground contact time + flight time). Typical error of measurement (TEM) and interclass correlations (ICC) were previously calculated with pilot data from 2 individuals experienced analyzing sprinting biomechanics to determine inter-rater reliability. Strong inter-rater reliability for these kinematic assessment methods were found for stride length (ICC = 0.99, TEM = 0.017 m), ground contact time (ICC = 0.95, TEM = 0.005 seconds), and flight time (ICC = 0.84, TEM = 0.003 seconds).

**Table 5.** Pearson's correlations between maximal velocity sprinting kinematics, anthropometric measures, and strength and power measures.*

| | | Height | Mass | Front squat/body mass | Power clean/body mass | Broad jump | Triple broad jump |
|---|---|---|---|---|---|---|---|
| Maximal sprinting velocity | Group | 0.18 | −0.70 | 0.47 | 0.80 | 0.79 | 0.78 |
| | Slow | −0.04 | −0.69 | 0.58 | 0.84 | 0.79 | 0.80 |
| | Fast | 0.03 | −0.21 | 0.23 | 0.60 | 0.28 | 0.39 |
| Stride rate | Group | −0.62 | −0.75 | 0.60 | 0.69 | 0.34 | 0.37 |
| | Slow | −0.46 | −0.51 | 0.60 | 0.59 | 0.26 | 0.33 |
| | Fast | −0.73 | −0.85 | 0.52 | 0.55 | −0.30 | −0.20 |
| Stride length | Group | 0.46 | 0.02 | −0.24 | 0.19 | 0.51 | 0.41 |
| | Slow | 0.66 | 0.03 | −0.33 | 0.14 | 0.50 | 0.41 |
| | Fast | 0.52 | 0.60 | −0.38 | −0.14 | 0.25 | 0.15 |
| Relative stride length | Group | −0.21 | −0.42 | 0.10 | 0.49 | 0.52 | 0.46 |
| | Slow | 0.20 | −0.20 | −0.09 | 0.37 | 0.55 | 0.48 |
| | Fast | −0.42 | −0.19 | 0.02 | 0.20 | −0.10 | −0.09 |
| Ground contact time | Group | 0.45 | 0.73 | −0.54 | −0.72 | −0.46 | −0.48 |
| | Slow | 0.27 | 0.56 | −0.60 | −0.69 | −0.37 | −0.42 |
| | Fast | 0.66 | 0.74 | −0.37 | −0.49 | −0.30 | 0.22 |
| Flight time | Group | 0.34 | 0.12 | −0.18 | −0.05 | 0.16 | 0.11 |
| | Slow | 0.32 | −0.08 | −0.03 | 0.13 | 0.16 | 0.13 |
| | Fast | 0.43 | 0.54 | −0.41 | −0.35 | 0.16 | 0.07 |

*The top number is the correlation for the whole group ($n = 40$), the middle number is the maximal velocity-slow group ($n = 20$), and the bottom number is the maximal velocity-fast group ($n = 20$).

Pilot data also revealed strong reliability within the testing sessions for ISV (ICC = 0.87, TEM = 0.08 $\text{m}\cdot\text{s}^{-1}$), MSV (ICC = 0.90, TEM = 0.17 $\text{m}\cdot\text{s}^{-1}$), acceleration GCT (ICC = 0.75, TEM = 0.005 seconds), acceleration FT (ICC = 0.75, TEM = 0.006 seconds), acceleration SL (ICC = 0.85, TEM = 0.026 m), maximal velocity GCT (ICC = 0.8, TEM = 0.003 seconds), maximal velocity FT (ICC = 0.82, TEM = 0.007 seconds), and maximal velocity SL (ICC = 0.7, TEM = 0.05 m).

**Table 6.** Changes in sprinting kinematics and different strength qualities over 1 year in elite rugby players ($n = 15$).

| Test | Pre | | Post | | $p$ value | Effect size (d) | Magnitude |
|---|---|---|---|---|---|---|---|
| Mass (kg) | 100.6 | ±11.3 | 101.8 | ±12.2 | 0.08 | 0.11 | Trivial |
| Triple broad jump (cm) | 8.18 | ±0.56 | 8.27 | ±0.57 | 0.08 | 0.16 | Trivial |
| Broad jump (m) | 2.55 | ±0.43 | 2.58 | ±0.42 | 0.11 | 0.06 | Trivial |
| Power clean (kg) | 121.7 | ±6.7 | 131.0 | ±8.2 | 0.002 | 1.39 | Very large |
| Relative power clean (kg·kg$^{-1}$) | 1.22 | ±0.13 | 1.30 | ±0.15 | 0.008 | 0.60 | Moderate |
| Front squat (kg) | 142.6 | ±14.3 | 145.9 | ±14.1 | 0.11 | 0.22 | Small |
| Relative front squat (kg·kg$^{-1}$) | 1.43 | ±0.20 | 1.45 | ±0.19 | 0.48 | 0.07 | Trivial |
| Acceleration fight time (s) | 0.07 | ±0.01 | 0.07 | ±0.01 | 0.30 | 0.19 | Trivial |
| Acceleration ground contact time (s) | 0.17 | ±0.02 | 0.16 | ±0.02 | 0.24 | 0.22 | Small |
| Acceleration stride length (m) | 1.22 | ±0.11 | 1.31 | ±0.09 | 0.003 | 0.81 | Large |
| Maximal velocity stride length (m) | 2.05 | ±0.11 | 2.08 | ±0.11 | 0.40 | 0.23 | Small |
| Maximal velocity ground contact time (s) | 0.11 | ±0.01 | 0.11 | ±0.01 | 0.95 | 0.01 | Trivial |
| Maximal velocity flight time (s) | 0.12 | ±0.01 | 0.12 | ±0.01 | 0.47 | 0.17 | Trivial |
| Initial sprint velocity (m·s$^{-1}$) | 5.73 | ±0.24 | 5.73 | ±0.27 | 0.99 | 0.00 | None |
| Maximal sprint velocity (m·s$^{-1}$) | 8.87 | ±0.59 | 8.85 | ±0.70 | 0.83 | 0.03 | Trivial |

**TABLE 7.** Pearson's correlation between changes in strength qualities and sprinting kinematics of elite rugby players ($n = 15$) over 1 year of training.

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mass | | | | | | | | | | | | | | |
| −0.47 | Triple broad jump | | | | | | | | | | | | | |
| 0.11 | 0.37 | Broad jump | | | | | | | | | | | | |
| 0.11 | −0.14 | −0.44 | Power clean | | | | | | | | | | | |
| −0.16 | 0.00 | −0.46 | 0.96 | Power clean/body mass | | | | | | | | | | |
| 0.13 | 0.15 | −0.41 | 0.56 | 0.48 | Front squat | | | | | | | | | |
| −0.30 | 0.37 | −0.40 | 0.45 | 0.49 | 0.90 | Front squat/body mass | | | | | | | | |
| 0.10 | −0.52 | −0.07 | 0.35 | 0.35 | −0.13 | −0.19 | Acceleration flight time | | | | | | | |
| 0.23 | −0.67 | −0.28 | 0.13 | 0.09 | −0.24 | −0.37 | 0.56 | Acceleration ground contact time | | | | | | |
| −0.17 | 0.09 | 0.37 | 0.13 | 0.13 | 0.23 | 0.31 | 0.28 | −0.15 | Acceleration stride length | | | | | |
| 0.03 | −0.10 | −0.38 | 0.70 | 0.70 | 0.54 | 0.48 | 0.36 | 0.34 | 0.25 | Maximal velocity stride length | | | | |
| 0.37 | 0.32 | 0.18 | 0.32 | 0.23 | 0.39 | 0.25 | −0.14 | −0.28 | −0.07 | 0.11 | Maximal velocity ground contact time | | | |
| 0.08 | −0.36 | −0.17 | −0.13 | −0.14 | −0.25 | −0.33 | 0.24 | 0.35 | 0.02 | 0.21 | −0.61 | Maximal velocity flight time | | |
| −0.28 | 0.42 | 0.03 | 0.14 | 0.21 | 0.41 | 0.49 | 0.09 | −0.07 | 0.43 | 0.41 | 0.01 | −0.10 | Initial sprint velocity | |
| −0.33 | 0.11 | −0.10 | 0.09 | 0.20 | 0.01 | 0.12 | 0.30 | 0.40 | 0.12 | 0.44 | −0.43 | 0.24 | 0.69 | Maximal sprint velocity |

### Strength Assessment

Within 1 week of the sprint testing, the participants were tested for strength qualities by assessing broad jump (BJ), triple broad jump (TBJ), power clean (PC), and front squat (FS) in a single session. The tests were performed in the following order: BJ, TBJ, PC, and FS with approximately 5 minutes between each exercise. Each of the participants was given 5 attempts for both BJ and TBJ. The score for each of the different jump conditions was the distance between the lines that the athlete started behind and the back of their heel after they had landed. During the BJ, the participants were encouraged to jump horizontally off of 2 feet as far as they could and were allowed to use an arm swing while jumping. While landing, the players were instructed to land in a position of deep knee flexion to maximize the horizontal distance of the jump. During the TBJ, the participants were encouraged to land in the same manner but with the exception that they land and jump again with a minimal landing time after the first and the second jumps. The longest jumps were retained for analysis. Pilot data of the jumping tests showed that they had high reliability with a TEM and Coefficient of Variation (CV) of 0.04 m and 7% for BJ and with 0.12 m and 7% for TBJ.

When testing for a 1 repetition maximum (1RM) PC and a 1RM FS, the subjects performed 2–3 warm-up sets of 3–5 repetitions below 60% followed by 1–2 repetitions at 70, 80, 85, 90, 95, and 100% of predicted 1RM. The subjects then continued to increase the weight by 2–5% until they failed. Each participant took 3–5 minutes between attempts at near maximal or maximal weights. The protocols for testing PC were that the bar had to begin from the floor and end when the athlete successfully stood up with the bar on their shoulders. The bar had to be received in the "power position" such that at no point did the long axis of their thigh drop below parallel. When testing FS, the athlete had to squat in a below parallel manner while keeping the bar on their shoulders and holding the bar in a "clean catch" position. Power clean and FS were expressed relative to BM (PC/BM and FS/BM) for analyzing relative strength.

### Training Program

All of the participants involved in part 2 of the study were training on a full-time basis at a national team training academy. Each of the participants were typically involved in approximately 8–12 weeks per year of national team duty, 24 weeks per year of club rugby, 12–16 weeks per year of preseason training and 4 weeks of rest. Training during national team competition weeks typically involved 1–2 strength and 3–4 rugby sessions per week. Club rugby weeks consisted of 2–3 strength, 1–2 speed, and 2–3 rugby sessions per week. Preseason was 2 speed, 3–4 strength, and 1–2 rugby sessions per week. Given the intense nature of rugby, each player was injured at some point of the study so that their training had to be modified, but no players were injured to an extent that

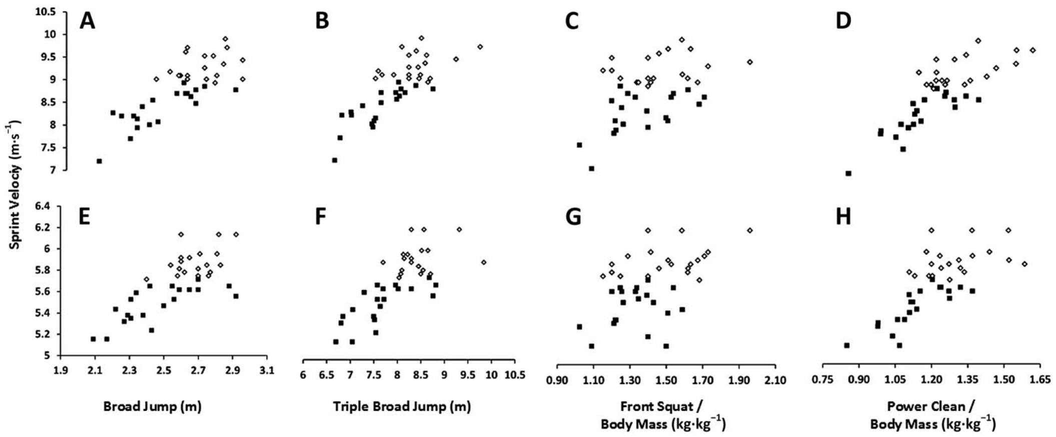

**Figure 1.** Scatterplots illustrating the relationships between maximal sprinting velocity (A–D) and initial sprinting velocity (E–H) with broad jump (A and E), triple broad jump (B and F), front squat relative to body mass (BM) (C and G), and power clean relative to BM (D and H). Slow group in each of the graphs is denoted by solid black squares, and the fast group in each graph is denoted by open diamonds.

long-term layoffs (>1 month) occurred. Each participant followed an individualized training program. Table 1 lists typical speed and strength exercises used during training sessions. When players were not involved in national team duty, each program typically went on 6- to 8-week cycles divided into an initial 3- to 4-week block emphasizing maximal strength with the second 3- to 4-week block emphasizing power. This was typically accomplished by altering training volumes of exercises (i.e., more back squats in block 1 and more plyometrics in block 2) or by replacing exercises (back squats in block 1 and jump squats in block 2). Speed training focused on improving acceleration in the first block of training and maximal sprinting velocity in the second block. Training during national team competition weeks was, at a minimum, focused on maintaining maximal, explosive, and reactive strength.

### Statistical Analyses

To assess the hypothesis that faster players had superior strength and power scores than their slower counterparts, the participants were, using the median split technique, divided into a fast group (*n* = 20) and a slow group (*n* = 20) for both acceleration (0- to 10-m split) and maximal velocity (30- to 40-m split). Fast and slow groups were compared for anthropometric scores, strength quality scores, and sprinting kinematics. Differences between the fast and slow groups

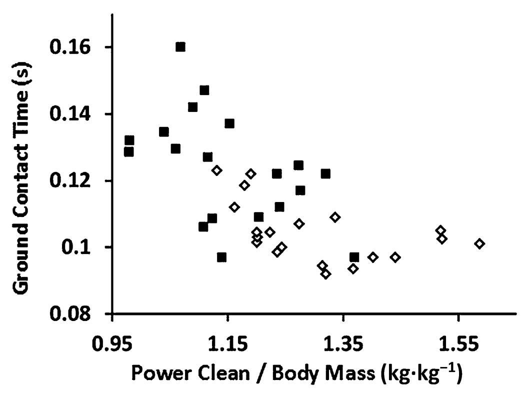

**Figure 2.** Scatterplot illustrating the relationship between power clean relative to body mass and maximal velocity ground contact time during a 40-m sprint. Slow group in the graph is denoted by solid black squares, and the fast group is denoted by open diamonds.

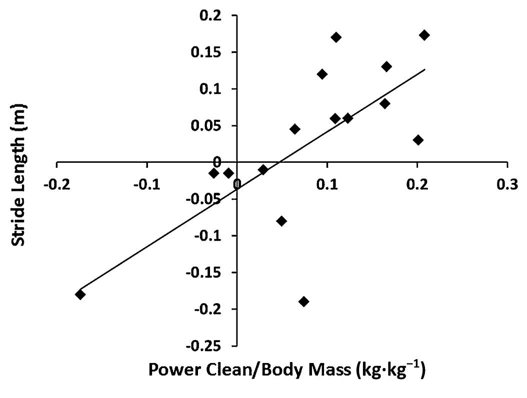

**Figure 3.** Correlation between changes (postscore-prescore) in maximal velocity stride length and increases in power clean relative to body mass over a 1-year period.

were calculated with Student's $t$-test. Cohen's $d$ effect sizes were calculated to characterize the differences between groups. To assess the relationships between the various sprinting kinematics, anthropometric, and strength quality measures in part 1, Pearson's correlations were calculated. In part 2, paired $t$-tests were used to compare the differences in testing scores between the pretests and posttests over the 1-year experimental period. To determine the transfer effect between strength and power exercises and sprinting performance, a transfer of training effect (42,45) was calculated according to the following formula:

$$\text{Transfer of Training Effect} = \frac{\text{Effect Size Change in Sprinting Performance}}{\text{Effect Size Change in Strength Training Exercise}}.$$

Transfer of training effects were only calculated between variables that had an effect size of at least $d = 0.2$ which is considered the smallest worthwhile difference for a team sport athlete (20). The higher the score of transfer of training effect, the more likely the training exercise positively influenced sprinting performance. Pearson's correlations were also calculated between the changes in various sprinting kinematics and strength and power scores over the 1-year period. The magnitude of positive correlations was classified as trivial <0.1, small 0.1–0.29, moderate 0.3–0.49, large 0.5–0.69, very large 0.7–0.89, and nearly perfect >0.9 (20). Cohen's $d$ effect sizes were considered trivial 0–0.19, small 0.2–0.59, moderate 0.6–1.19, large 1.2–1.99, and very large for >2.0 (20). All statistical analyses were conducted with XLSTAT (New York, NY, USA) software.

## RESULTS

In part 1, 13 athletes were placed in the fast group for both the acceleration and maximal velocity analyses, 13 were in both slow groups, and there were 14 athletes who were in one of the fast groups and one of the slow groups. Differences between the acceleration and maximal velocity groups for anthropometric measures, sprinting kinematics, and strength quality measures are listed in Tables 2 and 3, respectively. When comparing the fast and slow acceleration group, moderate differences for ground contact time (0.16 vs. 0.17 seconds, $d = 0.8$) and FS/BM (1.46 vs. 1.36 $kg \cdot kg^{-1}$, $d = 0.8$) were found. Large differences for PC/BM (1.30 vs. 1.14 $kg \cdot kg^{-1}$, $d = 1.2$), BJ (2.68 vs. 2.46 m, $d = 1.7$), and TBJ (8.44 vs. 7.54 m, $d = 1.7$). The fast and slow acceleration groups for maximal velocity showed moderate differences for stride length (2.06 vs. 1.99 m, $d = 0.8$), large differences for relative stride length (1.13 vs. 1.07 $m \cdot m^{-1}$, $d = 1.3$), PC/BM (1.30 vs. 1.14 $kg \cdot kg^{-1}$, $d = 1.2$), BJ (2.69 vs. 2.45 m, $d = 1.8$), and TBJ (8.44 vs. 7.66 m, $d = 1.5$), and very large differences for ground contact time (0.10 vs. 0.12 seconds, $d = 2.1$).

The correlations between anthropometric measures and strength quality scores with sprinting kinematics for the whole group, fast group, and slow group are displayed in Figures 1 and 2 and Tables 4 and 5. Initial sprint velocity has similar correlation for both the slow and fast group with PC/BM

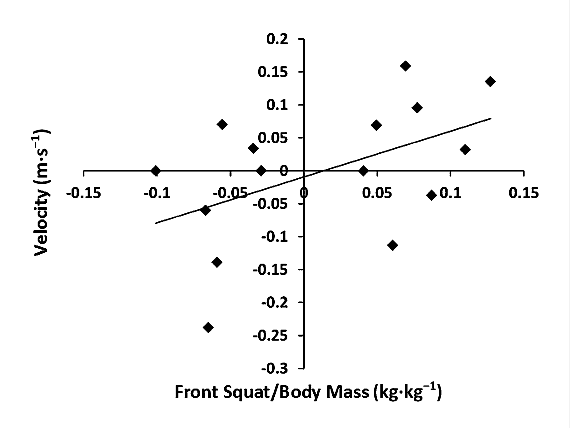

**Figure 5.** Correlation between changes (postscore-prescore) in initial sprinting velocity and front squat relative to body mass over a 1-year period.

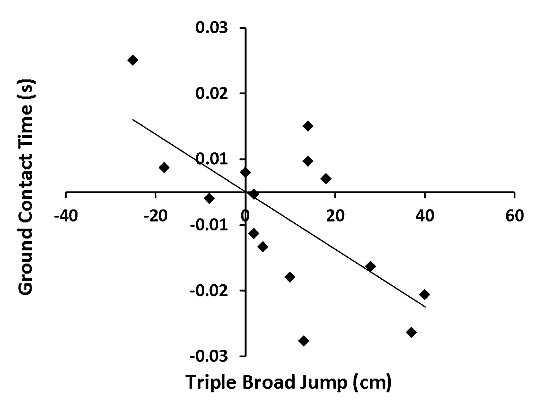

**Figure 4.** Correlation between changes (postscore-prescore) in acceleration ground contact time and triple broad jump over a 1-year period.

($r = 0.68$, $r = 0.67$), BJ ($r = 0.73$, $r = 0.66$), and TBJ ($r = 0.72$, $r = 0.69$). The slow group, when compared with the fast group, had stronger correlations between MSV and FS/BM ($r = 0.58$, $r = 0.28$), PC/BM ($r = 0.84$, $r = 0.60$), BJ ($r = 0.79$, $r = 0.28$), and TBJ ($r = 0.80$, $r = 0.39$). Of all the strength tests, PC/BM had the strongest relationship with acceleration ground contact time ($r = -0.61$, $r = -0.56$) and maximal velocity ground contact time ($r = -0.69$, $r = -0.49$) with the slow and fast groups.

Changes in strength and speed measurement are presented in Table 6, and the correlations between those changes are presented in Table 7. Changes in PC/BM and FS/BM had very large ($r = 0.70$) and moderate correlations ($r = 0.49$) with change in stride length over 1 year. Changes in FS/BM had a moderate relationship ($r = 0.49$) with changes in ISV. For determining transfer of training effects, PC/BM was the only strength quality measure and acceleration stride length, acceleration ground contact time, and maximal stride length were the only sprinting kinematics that met the criteria of at least a small ($d = 0.2$) effect size change. The transfer of training effects was therefore calculated between PC/BM and acceleration stride length (1.2), acceleration ground contact time (0.36), and maximal velocity stride length (0.38) (Figures 3–5).

## DISCUSSION

The results of this study indicated that the fast groups for both acceleration and maximal velocity displayed better scores in the different strength qualities (Tables 2 and 3). Large differences ($>d = 1.2$) favoring the fast groups over the slow groups were found for PC/BM, TBJ, and BJ (Tables 2 and 3). Front squat or BM did not seem to be as good as a discriminator with only a small difference between the maximal velocity groups ($d = 0.5$) and a moderate difference ($d = 0.8$) in the acceleration groups. This is consistent with the results of Hori et al. (21) who found that a group of athletes with relatively high PC/BM scores were faster over 10 m than a group who had relatively lower PC/BM scores. Peak power and velocity in jump squats (14) and horizontal jumps, drop jumps, and back squat relative to BM (24) have also previously differentiated fast groups from slow groups over 10 m.

Given the importance of low ground contact times for high velocities during the acceleration phase of a sprint (24), it is logical that powerful athletes who can develop force quickly (38) will have shorter ground contact times and be faster over 10 m than their weaker peers. Ground contact time was the only sprinting kinematic measure with at least a moderate difference (0.01 seconds, $d = 0.8$) between the acceleration-fast group and the acceleration-slow group, which is similar to other results highlighting its importance (26,30). The fact that stride length showed only a small difference highlights that acceleration is dependent on developing optimal impulse and an optimal force vector (22,25). Maximal sprinting velocity on the other hand has been shown to be dependent on developing the necessary vertical forces while minimizing ground contact time (39). The results of this study supported this with a very large difference (0.02 seconds, $d = 2.1$) in ground contact time between the maximal velocity-fast group and maximal velocity-slow group. There was a moderate and large difference between stride length (0.07 m, $d = 0.8$) and relative stride length (0.05 $\text{m} \cdot \text{m}^{-1}$, $d = 1.3$) between the maximal velocity-fast group and maximal velocity-slow group, which underscores the importance of stride length as the second most important kinematic factor after ground contact time.

An interesting observation in part 1 of this study was that there were weaker correlations between maximal sprinting velocity and the strength quality tests for maximal velocity-fast group when compared with maximal velocity-slow group (Table 3 and Figure 1). The correlations between ISV with BJ, TBJ, PC/BM, and FS/BM, however, were generally the same for the acceleration-fast group and acceleration-slow group (Table 3). These differences could possibly be explained by ground contact time during the different phases of sprinting. The acceleration ground contact time of both the acceleration-fast group and acceleration-slow group is similar at 0.16 and 0.17 seconds. The maximal velocity ground contact times for the maximal velocity-fast group and maximal velocity-slow group, however, were much shorter at 0.12 and 0.10 seconds. The time to develop force may be the limiting factor for the potential of strength and power exercises to improve sprinting speed. For instance, PC/BM had similar associations with ground contact times for both the acceleration-slow group ($r = -0.61$) and acceleration-fast group ($r = -0.56$) (Table 4). However, PC/BM had a much weaker relationship with ground contact time for the maximal velocity-fast group ($r = -0.37$) when compared with maximal velocity slow-group ($r = -0.60$) (Figure 2 and Table 5). This implies that the specificity of an exercise and its potential to improve sprinting speed may be different between fast and slow athletes because of differences in ground contact time. Selecting exercises that help increase the rate of force development in less than 0.10 seconds may be highly important for improving maximal sprinting velocity in players that are already capable of achieving high sprinting speeds (44).

Despite taking part in strength training activities year round, the average improvements of lower-body strength qualities of the athletes in part 2 of this study were generally low (Table 6). This is similar to other previously reported data that showed no improvements over the course of a year in the development of leg strength in professional rugby players (1). The extensive strength training background, heavy competition schedules, and short-term injury layoffs likely contributed to this. The exception to this was PC, which showed a large average improvement (121–131 kg, $p = 0.002$, $d = 0.55$) in the group (Table 6). Several of the athletes did make large improvements in all of the different tests, whereas others actually showed decreases, which resulted in the trivial mean improvement of the group as a whole.

The cross-sectional data from part 1 suggest that increasing all of the different strength qualities would increase sprinting speed, and this would most likely happen by decreasing ground contact times. Interestingly, the correlation between changes in PC/BM over 1 year and changes in ground contact time during acceleration ($r = 0.09$) and maximal velocity ($r = 0.23$) sprinting were low and in the opposite direction of what was expected. Changes in maximal velocity stride length, however, had a very large relationship with the change in PC/BM ($r = 0.70$). Unexpectedly, changes in PC/BM ($r = 0.20$), FS/BM ($r = 0.12$), BJ ($r = -0.10$), and TBJ ($r = 0.11$) all had small or trivial relationships with the changes in MSV. Changes in FS/BM did have a moderate relationship ($r = 0.49$) with the change in ISV though. These relationships highlight the problematic nature of using cross-sectional correlations to predict the effectiveness of training exercises for improving performance. The separate analyses of faster and slower groups, combined with the longitudinal analysis of this study, further demonstrate the importance of recognizing the athletes with different training ages likely to have different adaptation potential to specific strength training stimuli. The physiological qualities that underpin success in sprinting and strength and power training may be similar but with reduced or even minimal remaining trainability or transfer potential in elite athletes with extensive training backgrounds. Strength and power training in athletes with minimal strength training background should improve neural drive to agonist muscles and improve stretch reflexes and intramuscular coordination (34,35). This would likely improve sprinting performance by decreasing ground contact time (33) through an increased rate of force development (7,40). However, the principle of diminishing returns may mean that this strategy is no longer effective in highly trained athletes.

The fact is that only 2 athletes were able to decrease maximal velocity ground contact time over an entire year (both −0.01 seconds) that may be explained by the following possibilities. The high training load and fatigue from competitions and rugby practices may have prevented any positive adaptations to the speed and power training for many of the athletes. The exercises selected for speed and strength training (Table 1) sessions may also have been inadequate for improving sprinting speed in these players. Another possibility is that there is a limitation on the ability to develop force at high velocities. Fascicle length of hamstring muscles has previously been shown to discriminate between different levels of sprinters (23). The force-velocity relationship of these key sprinting muscles (29) likely has a structural limit of how much it can be improved and this probably affects the potential for strength and power training to impact maximal velocity sprinting performance. It may be the case that fascicle lengths of hamstring muscles dictate the velocity at which hip extension in sprinting can happen but greater force can be developed at that velocity through training, and this allows for an improved stride length at maximal velocity. Increases in PC/BM ($r = 0.70$) and FS/BM ($r = 0.48$) both indeed did seem to predict changes in maximal velocity stride length.

Interestingly, there was a moderate relationship between the changes of acceleration ground contact time and TBJ ($r = -0.67$). Successful acceleration ability has typically been described by optimizing force vectors (22,25) through a forward lean. It then follows that improvement in TBJ that combines an emphasis on brief contact times while jumping with a forward lean would be associated with improvements in acceleration ground contact time. Even though the associations between changes in acceleration stride length and each of the strength quality tests were all weak, the high transfer of training effect (1.33) calculated between PC/BM and acceleration stride length indicated that improving concentric lower-body explosive strength is beneficial for improving stride length during the first few steps from a standing start.

The frequent sprints that take place during rugby games mean that acceleration is likely an important physical ability for all players (11,12). In highly trained rugby players, continuing to train lower-body explosive strength and combining it with exercises to learn to optimize the resultant force vector such as horizontal jumps and sled sprints (16) is probably the key for developing acceleration ability. It is unlikely that athletes with extensive strength training backgrounds will find that strength and power training results in improvements in maximal sprinting velocity through a decrease in ground contact time but possibly through an increase in stride length. Improving lower-body maximal and explosive strength may improve acceleration ability through an increase in stride length. It is important to realize that cross-sectional correlations may highlight some shared physiological qualities between strength and power exercises and sprinting ability, but these qualities may no longer be trainable in a manner that leads to transfer. It may be possible that rugby players with limited time for strength and conditioning activities are strong enough for their position. For instance, a winger, whose position depends on high levels of sprinting speed, may have adequate lower-body strength (i.e., PC of 150% of BM) to sprint at very high velocities, tackle, ruck, etc. Their training time may need to be devoted to trying to increase sprinting speed through extra speed sessions and perform only a maintenance level frequency of strength training sessions. A prop, however, may need to continue to focus much of their efforts on increasing strength because scrummaging is critical for their position, and maximal strength (32) is critical for scrummaging. Simple field tests like the ones used in this study or more complex tests that use force plates such as mid-thigh isometric pulls, drop jumps, and countermovement jumps can be used to gain a more complete physical profile of athletes. These tests can then be used to individualize exercise selection when designing strength training programs. Exercise selection is paramount for strength and conditioning coaches working with elite rugby players given the small possibility for further training adaptation (2) as well as the limited amount of strength and conditioning sessions possible because of competition schedules (1) and injuries (13) that interrupt training. It would be beneficial for future research to explore how the sequencing of exercises in training and the arrangement of training sessions during the week affect physical development.

## Practical Applications

Although the majority of athletes can experience improvements in sprinting ability through improving general maximal strength, the results of the current study suggest that the notion of improving maximal sprinting speed of highly trained rugby players through increasing strength is more complex. Cross-sectional data indicate that increasing strength should lead to a decrease in maximal velocity ground contact time and subsequent increases in maximal sprinting speed. The results of this study would indicate that it is difficult to decrease ground contact time in highly trained athletes and improving strength corresponds to an increase in maximal velocity stride length rather than a decrease in ground contact time. Improving different strength qualities such as concentric explosive strength and reactive strength do seem to correspond to an improvement in stride length and ground contact during the first steps of a sprint from a standing start. Achieving high levels of maximal, explosive, and reactive strength is important for elite rugby players, even if it does not result in direct transfer to sprinting speed of players with an extensive training background. It is likely rugby players with an extensive training history will reach a point of diminishing returns where their lower-body strength is high enough to sprint at high velocities. If improving sprinting speed is the goal of rugby players who already possess substantial lower-body strength, their training focus may need to shift from improving general strength qualities to maintain their current strength level so that their training can have a greater focus on speed training.

## References

1. Appleby, B, Newton, R, and Cormie, P. Changes in strength over a two year period in professional rugby union players. *J Strength Cond Res* 26: 2538–2546, 2012.
2. Baker, DG. 10-year changes in upper body strength and power in elite professional rugby league players-the effect of training age, stage and content. *J Strength Cond Res* 27: 285–292, 2013.
3. Baker, D and Nance, S. The relation between running speed and measures of strength and power in professional rugby league players. *J Strength Cond Res* 13(3): 230, 1999.
4. Barr, MJ and Nolte, VW. Which measure of drop jump performance best predicts sprinting speed? *J Strength Cond Res* 25: 1976–1982, 2011.
5. Barr, MJ, Sheppard, JM, and Newton, RU. Sprinting kinematics of elite rugby players. *J Aust Strength Cond* 21(4): 14–20.
6. Brechue, W, Mayhew, J, and Fontaine, P. Characteristics of sprint performance in college football players. *J Strength Cond Res* 24: 1169–1178, 2010.
7. Burgess, K, Connick, M, Graham-Smith, P, and Pearson, SJ. Plyometric vs. isometric training influence on tendon properties and muscle output. *J Strength Cond Res* 21: 986–989, 2007.
8. Comfort, P, Bullock, N, and Pearson, SJ. A comparison of maximal squat strength and 5-, 10-, and 20-meter sprint times, in athletes and recreationally trained men. *J Strength Cond Res* 26: 937–940, 2012.
9. Comfort, P, Haigh, A, and Matthews, M. Are changes in maximal squat strength during preseason training reflected in changes in sprint performance in rugby league players? *J Strength Cond Res* 26: 772–776, 2012.
10. Delecluse, C, Van Coppenolle, H, Willems, E, Van Leemputte, M, Diels, R, and Goris, M. Influence of high-resistance and high-velocity training on sprint performance. *Med Sci Sport Exer* 27: 1203–1209, 1995.
11. Duthie, G, Pyne, D, Marsh, D, and Hooper, S. Sprint patterns in rugby union players during competition. *J Strength Cond Res* 20: 208–214, 2006.
12. Duthie, G. A framework for the physical development of elite rugby union players. *Int J Sports Physiol Perform* 1: 2–13, 2006.
13. Fuller, C, Sheerin, K, and Targett, S. Rugby World Cup 2011: international rugby board injury surveillance study. *Br J Sports Med* in press.
14. Hansen, KT, Cronin, JB, Pickering, SL, and Douglas, L. Do force-time and power-time measures in a loaded jump squat differentiate between speed performance and playing level in elite and elite junior rugby union players? *J Strength Cond Res* 25: 2382–2391, 2011.
15. Harris, GR, Stone, MH, Bryant, H, Proulx, CM, and Johnson, RL. Short-term performance effects of high power, high force, or combined weight-training methods. *J Strength Cond Res* 14: 14–20, 2000.
16. Harrison, AJ and Bourke, G. The effect of resisted sprint training on speed and strength performance in male rugby players. *J Strength Cond Res* 23: 275–283, 2009.
17. 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.
18. Hermassi, S, Chelly, MS, Tabka, Z, and Shephard, RJ. Effects of 8-week in-season upper and lower limb heavy resistance training on the peak power, throwing velocity, and sprint performance of elite male handball players. *J Strength Cond Res* 25: 2424–2433, 2011.
19. Higham, DG, Pyne, D, Anson, J, and Eddy, A. Physiological, anthropometric, and performance characteristics of rugby sevens players. *Int J Sports Physiol Perform* 8: 19–27, 2013.
20. Hopkins, WG. A new view of statistics. 2011. Available at: www.sportsci.org/resource/stats. Accessed January 2012.
21. Hori, N, Newton, R, Andrews, W, Kawamori, N, McGuigan, MR, and Nosaka, K. Does performance of hang power clean differentiate performance of jumping, sprinting, and changing of direction? *J Strength Cond Res* 22: 412–418, 2008.
22. Kugler, F and Janshen, L. Body position determines propulsive forces in accelerated running. *J Biomech* 43: 343–348, 2010.
23. Kumagai, K, Abe, T, Brechue, W, Ryushi, T, Takano, S, and Mizuno, M. Sprint performance is related to muscle fascicle length in male 100-m sprinters. *J Appl Phys* 88: 811–816, 2000.
24. Lockie, RG, Murphy, AJ, Knight, TJ, and de Jonge, X. Factors that differentiate acceleration ability in field sport athletes. *J Strength Cond Res* 25: 2704–2714, 2011.
25. Lockie, RG, Murphy, AJ, Schultz, AB, Jeffriess, MD, and Callaghan, SJ. Influence of sprint acceleration stance kinetics on velocity and step kinematics in field sport athletes. *J Strength Cond Res* 27: 2494–2503, 2013.
26. Mann, R. *The Mechanics of Sprinting and Hurdling*. Lexington, KY: CreateSpace 2011.

27. McEvoy, KP and Newton, RU. Baseball throwing speed and base running speed: the effects of ballistic resistance training. *J Strength Cond Res* 12: 216, 1998.
28. Mero, A. Relationship between the muscle fiber characteristics, sprinting and jumping of sprinters. *Biol Sport* 2: 155–162, 1985.
29. Miller, RH, Umberger, BR, and Caldwell, GE. Limitations to maximum sprinting speed imposed by muscle mechanical properties. *J Biom* 45: 1092–1097, 2012.
30. Murphy, AJ, Lockie, RG, and Coutts, AJ. Kinematic determinants of early acceleration in field sport athletes. *J Sci Med Sport* 6: 534, 2003.
31. Peterson, MD, Alvar, BA, and Rhea, MR. The contribution of maximal force production to explosive movement among young collegiate athletes. *J Strength Cond Res* 20: 867–873, 2006.
32. Quarrie, KL and Wilson, BD. Force production in the rugby union scrum. *J Sports Sci* 18: 237–246, 2000.
33. Rimmer, E and Sleivert, G. Effects of a plyometrics intervention program on sprint performance. *J Strength Cond Res* 14(3): 295–301, 2003.
34. Ross, A, Leveritt, M, and Riek, S. Neural influences on sprint running: training adaptations and acute responses. *Sports Med* 31: 409–425, 2001.
35. Semmler, J and Enoka, R. Neural contributions to changes in muscle strength. In: *Biomechanics in Sports*. V. Zatsiorsky, ed. Oxford, United Kingdom: Blackwell Science, 2000. pp. 3–20.
36. Sleivert, G and Taingahue, M. The relationship between maximal jump-squat power and sprint acceleration in athletes. *Eur J Appl Physiol* 46–52, 2004.
37. Stone, MH, Stone, M, and Sands, WA. *Principles and Practice of Resistance Training*. Champaign, IL: Human Kinetics, 2007.
38. Tillin, NA, Thomas, M, Pain, G, and Folland, J. Explosive force production during isometric squats correlates with athletic performance in rugby union players athletic performance in rugby union players. *J Sports Sci* 31: 66–76, 2013.
39. Weyand, P, Sandell, R, Prime, D, and Bundle, M. The biological limits to running speed are imposed from the ground up. *J Appl Physiol* 108: 950–961, 2010.
40. Wilson, G, Murphy, A, and Giorgi, A. Weight and plyometric training: effects on eccentric and concentric force production. *Can J Appl Physiol* 21: 301–315, 1996.
41. Wisloff, U, Castagna, C, Helgerud, J, Jones, R, and Hoff, J. Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *Br J Sports Med* 38: 285–288, 2004.
42. Young, WB. Transfer of strength and power training to sports performance. *Int J Sports Physiol Perform* 1(2): 74–83, 2006.
43. Young, W, Benton, D, Duthie, G, and Pryor, J. Resistance training for short sprints and maximum-speed sprints. *Strength Cond J* 23: 7–13, 2001.
44. Young, W, Mclean, B, and Ardagna, J. Relationship between strength qualities and sprinting performance. *J Sport Med Phys Fit* 35: 13–19, 1995.
45. Zatsiorsky, V and Kraemer, WJ. *Science and Practice of Strength Training*. Champaign, IL: Human Kinetics, 2006.