THE EFFECTS OF DIFFERENT SPEED TRAINING PROTOCOLS ON SPRINT ACCELERATION KINEMATICS AND MUSCLE STRENGTH AND POWER IN FIELD SPORT ATHLETES

ROBERT G. LOCKIE,[1] ARON J. MURPHY,[2] ADRIAN B. SCHULTZ,[1] TIMOTHY J. KNIGHT,[1] AND XANNE A.K. JANSE DE JONGE[1]

[1]Exercise and Sport Science, School of Environmental and Life Sciences, University of Newcastle, Ourimbah, Australia; and [2]Human Movement Department, School of Leisure, Sport and Tourism, University of Technology, Sydney, Australia

ABSTRACT

Lockie, RG, Murphy, AJ, Schultz, AB, Knight, TJ, and Janse de Jonge, XAK. The effects of different speed training protocols on sprint acceleration kinematics and muscle strength and power in field sport athletes. *J Strength Cond Res* 26(6): 1539–1550, 2012—A variety of resistance training interventions are used to improve field sport acceleration (e.g., free sprinting, weights, plyometrics, resisted sprinting). The effects these protocols have on acceleration performance and components of sprint technique have not been clearly defined in the literature. This study assessed 4 common protocols (free sprint training [FST], weight training [WT], plyometric training [PT], and resisted sprint training [RST]) for changes in acceleration kinematics, power, and strength in field sport athletes. Thirty-five men were divided into 4 groups (FST: $n = 9$; WT: $n = 8$; PT: $n = 9$; RST: $n = 9$) matched for 10-m velocity. Training involved two 60-minute sessions per week for 6 weeks. After the interventions, paired-sample *t*-tests identified significant ($p \leq 0.05$) within-group changes. All the groups increased the 0- to 5-m and 0- to 10-m velocity by 9–10%. The WT and PT groups increased the 5- to 10-m velocity by approximately 10%. All the groups increased step length for all distance intervals. The FST group decreased 0- to 5-m flight time and step frequency in all intervals and increased 0- to 5-m and 0- to 10-m contact time. Power and strength adaptations were protocol specific. The FST group improved horizontal power as measured by a 5-bound test. The FST, PT, and RST groups all improved reactive strength index derived from a 40-cm drop jump, indicating enhanced muscle stretch-shortening capacity during rebound from impacts. The WT group increased absolute and relative strength measured by a 3-repetition maximum squat by approximately 15%. Step length was the major limiting sprint performance factor for the athletes in this study. Correctly administered, each training protocol can be effective in improving acceleration. To increase step length and improve acceleration, field sport athletes should develop specific horizontal and reactive power.

KEY WORDS sprint training, plyometrics, resisted sprinting, weight training, biomechanics

INTRODUCTION

Attaining a high sprint velocity over a short distance is vital for successful performance in team and field sports (e.g., American football, rugby, soccer, Australian Rules football) (33). Accelerating from a stationary position or a moving start requires high force generation capacity to overcome the body's inertia. Thus, training techniques involving a high external resistance are useful for developing acceleration (15). When training for field sports, it is important that any gains resulting from strength and power training are translated into performance-specific movements, such as sprinting. Forms of resistance training techniques used for strength, power, and speed development, in addition to free sprint training (FST), include weights training, plyometrics, and resisted sprinting. Although the effects of these protocols have previously been investigated, there is still uncertainty in regards to the specific mechanisms of improvement.

Free sprint training, or sprint training without the use of any external equipment, forms the basis for most speed training programs. Free sprint training has been shown to increase running velocity over short distances (i.e., 15–20 m) (22,25,37), vertical power as measured by a countermovement jump (CMJ) (25,37), horizontal power as measured by a standing long jump (25), and a 5-bound test (5BT) (37). Markovic et al. (25) also found that 10 weeks of FST increased isometric force production during a bilateral squat

Address correspondence to Robert G. Lockie, robert.lockie@newcastle.edu.au.

26(6)/1539–1550

Journal of Strength and Conditioning Research

in male physical education students. To date, the effects of FST on initial acceleration step characteristics have not been conclusively investigated. Kristensen et al. (22) measured stride length and frequency during a 22-m sprint in trained subjects, but they did not measure the initial 2 m. Given the importance of the first few meters of a sprint (31), biomechanical analyses are an important tool for assessing the first few steps of a short sprint.

Doubt remains as to whether the movements used during typical resistance training exercises (i.e., strength- and power-based activities) are specific to field sport acceleration. Resistance training with weights has been shown to improve 10-m sprint performance in field sport athletes (9) but showed no significant effect in physically active men (28). Research investigating the effects of plyometrics training has also shown conflicting results. Sprint performance over 10 m in physical education students (12), and rugby union players (34), improved after a plyometrics intervention. However, plyometrics training did not enhance 4- and 12-m sprint performance in novice tennis players (35). The mechanisms underpinning how either weights or plyometrics training could benefit acceleration are unspecified. Further research needs to define if typical lower-body weights training only or plyometrics training can ultimately improve sprint acceleration and the technical mechanisms by which this may occur.

Resisted sprinting overloads an athlete in movements similar to free sprinting. Potentially, these techniques could increase lower-limb muscular force output, leading to training adaptations, which may lead to changes in step characteristics (e.g., increased step length) over time, and increases in strength and power (13). Resisted sprint training can improve sprint acceleration in field sport athletes (17,37). Furthermore, Harrison and Bourke (17) have also shown that resisted sprint training (RST) can improve force development during a squat jump in rugby union players, while also stimulating stretch-shortening cycle capabilities as measured by drop jump performance. However, the kinematic mechanisms responsible for the increase in velocity from RST (i.e., changes in step length and frequency, contact and flight time), and any changes to absolute and relative strength, remain undefined.

Although there may be general agreement that these training protocols can improve sprinting speed, the mechanisms of this improvement, particularly in relation to movement kinematics and how increased strength and power can affect technique, are yet to be acceptably quantified. Because of the popularity of these protocols, this is a major issue for strength and conditioning coaches and sport scientists alike. This study will determine the effects that different speed training protocols (free sprinting, weights, plyometrics, and resisted sprinting) have upon sprint acceleration kinematics, strength, and power in field sport athletes. The purpose of this study is not to compare the protocols with each other, because they are rarely used in isolation in general strength and conditioning practice. Rather, this study will document the specific technical adaptations that result after the implementation of FST, weight training (WT), plyometric training (PT), and RST. It is hypothesized that free sprint training will encourage movement technique adaptations, with negligible changes to strength and power performance; WT will increase strength, and this will manifest in sprint technique through an increase in step length; plyometrics training will increase power, and as a result, there will be improvements in step length and the capabilities related to speed of movement (i.e., step frequency, contact time), and RST will cause an increase in strength specific to the sprint step, which will be shown through positive changes to sprint technique (i.e., increased step length). With a more definitive understanding of the changes induced by these modalities, training practices can become more specific for field sport athletes.

METHODS

Experimental Approach to the Problem

This investigation aimed to establish the effects of 4 training protocols targeting the development of sprint acceleration–free sprinting, weights, plyometrics, and resisted sprinting. To identify protocol-specific adaptations, within-group changes were the focus. As stated previously, this study did not attempt to compare protocols, or define the superiority of one protocol over another, because they are rarely used in isolation in the training of field sport athletes. Instead, this study will define the effects these protocols have upon speed, power, and strength and thus provide necessary information for the strength and conditioning professional to assimilate when composing a field and team sport athlete's training program. This investigation required the subjects to perform speed, power, and strength tests before and after a 6-week training program involving 1 of the 4 protocols. In pretesting and posttesting, the subjects completed 10-m sprints that were filmed and timed for kinematic analysis; bounding (5BT) and jump (CMJ and 40-cm drop jump) tests for lower-limb power analysis; and a 3-repetition maximum (3RM) squat strength assessment. The testing was conducted over 2 days, with the maximum strength assessment isolated on day 2. Dependent variables included sprint velocity, step length and frequency, contact and flight time, over the selected intervals of 0–5, 5–10, and 0–10 m; bounding distance and jump heights as indirect measures of power; and maximum load lifted in the squat assessment expressed in absolute (kilograms) and relative (3RM·per body mass) terms. The reliability of the data collection procedures used in this study has been previously established (23).

Subjects

Thirty-five men (age = 23.1 ± 4.2 years; height = 1.82 ± 0.1 m; mass = 83.1 ± 8.6 kg) volunteered to participate in this study. The subjects were recruited if they (a) were currently participating in a field sport; (b) had a strength training history (≥2 times per·week) extending over the previous year; (c) were currently strength training (≥3 $h \cdot wk^{-1}$); (d) did not have any medical conditions compromising participation; (e) agreed to follow a predetermined training program; and (f) continued with their normal physical activity (27,37). The study was conducted during the winter competition season of the major football codes (17,37). This generally consisted of 2 field-based and 2 gymnasium-based training sessions per week and 1 football game per week (37). The methodology and procedures used in this study were approved by the institutional ethics committee. All the subjects received a clear explanation of the study, including the risks and benefits of participation, and written informed consent was obtained before testing.

Sample size was determined by estimating the magnitude of differences between the effect sizes that would theoretically result from the training protocols. Because effect size may be measured in relation to the principle assessment criterion, 0- to 10-m velocity was used. Based on research examining sprint acceleration training (37), it was assumed that the effect size for this study would be large (0.8). An 80% confidence level was desired, and power was set at 0.8. Consequently, with an expected effect size of 0.8 and alpha level of 0.05, the sample size used in the study was considered adequate to determine velocity changes with sufficient statistical power (21).

Procedures

Testing was conducted over 2 days, separated by 48 hours. Day 1 included the acceleration assessment, which involved four 10-m sprints filmed and timed for kinematic analysis. This 10-m distance is indicative of the initial acceleration phase important to field sport athletes (14,36). Power assessment, consisting of bounding, CMJs and drop jumps, followed the speed testing. Day 2 was the strength assessment, which involved a 3RM squat. Before data collection on day 1, the subject's age, height, and mass were recorded. Body mass index (BMI; height$\cdot$[body mass^2]$^{-1}$) was used to monitor any changes in physical characteristics over the training period. The subjects were examined before and after the 6 weeks of training. Posttesting was conducted within a week of the subject's final session. The subjects refrained from intensive exercise in the 24 hours before each testing occasion.

Speed Analysis

Each subject completed four 10-m sprints on day 1. A Super-VHS high-speed video camera (Vicon/Peak Performance Technologies, Englewood, CO, USA), with a sampling rate of 200 Hz, filmed each sprint. The camera was positioned 8.75 m lateral to the subject, allowing a sagittal plane view. The camera and stand were positioned at a height of 0.79 m. The 0- to 5-m interval was filmed during the first 2 sprint trials, and the 5- to 10-m interval was filmed in the second 2 trials. For the 0- to 5-m interval, the camera was placed at 2.5 m, and for the 5- to 10-m interval, it was placed 7.5 m from the start line. Markers were positioned at 10 m to signify the finish line. Two portable 500-W lights (Fairway Lighting©, Melbourne, Australia) provided external illumination. Before testing, a meter-long bar was carried throughout the observation volume and imaged by the camera (16). These data were analyzed to ensure that the recordings were calibrated and representative of the real-space coordinate system. As per previous sprint research, 2 trials were used per interval (5,23,24,37). The subjects were allowed to start in their own time and were instructed to sprint through the finish line. Rest periods of 2 minutes were allocated between sprint trials.

Reflective tape was placed on the subject's shoes on the fifth metatarsal for the right foot and the first metatarsal for the left foot. These selected landmarks were determined through palpation through the shoes and permitted the calculation of step length, step frequency, and contact time. Recorded images were collected on a video cassette, transferred onto an IBM-compatible computer via Studio Digital Video (version 1.1.0.15.), and edited in Adobe Premiere 6.0. The edited file was then exported into custom software (DigiSport 2000, BBSportz version 0.5.2.01) for further analysis. Analysis was performed on the 2 trials used for each interval, and the averages were used for further analysis. The total number of steps and contacts a subject had within an interval was used to calculate mean step kinematics. Start and finish points of the movement phases were estimated visually from the video footage (4). Step length was the distance between toe-off of one foot, and touchdown (foot-strike) of the contralateral foot. Step frequency was calculated from the velocity and mean step lengths for each interval through the following equation: step frequency = velocity$\cdot$mean step length per interval^{-1} (19). Contact time was the period between touchdown and toe-off of the one foot during ground support. Flight time was the duration between toe-off of the 1 foot and touchdown of the contralateral foot.

The time taken for the sprints was measured by a velocimeter (Onspot©, Wollongong, Australia). The velocimeter incorporated a stopwatch (Seiko©, Tokyo, Japan) and a nylon line attached to a reel, which allowed the line to unwind unimpeded when the subject began sprinting. An optical sensor sent electrical impulses to the velocimeter's processor for every 0.1 m of linear displacement of the line. For each trial, the velocimeter was placed 1.5 m behind the subject on a table that was 0.72 m in height. The line was attached to the back of the subject's shorts, and the stopwatch was activated with the first movement of the subject. The subjects were instructed not to hesitate at the start of their sprint, because this would falsely trigger the velocimeter. If a subject falsely triggered the timer, the trial was disregarded, and another attempt was allowed after the requisite rest period. The recorded times for the 3 chosen intervals (0–5, 5–, and 0–10 m) were then used to calculate velocity through the following equation: velocity = displacement$\cdot$time^{-1}.

Lower-Limb Power Assessment

In addition to the speed analysis, day 1 also included the assessment of lower-limb power. Bounding distance and jump heights have been previously used as estimates of lower-limb power (17,25,37). For each separate power assessment, 3 trials were completed with 2 minutes of recovery time allocated between trials, and the average was used for analysis.

The 5BT was used to measure the stretch-shortening cycle capacity in the horizontal plane. This test involved the subjects attempting to cover the greatest horizontal distance possible by performing a series of 5 forward bounds with alternate right and left foot contacts. The subjects were required to start with both feet parallel, before commencing with the 5 alternate-leg bounds. They were allowed to choose the preferred leg to perform the initial push-off with, and this was consistent for all trials. Total distance covered was measured from the start line to the final position of the front of the landing foot on the fifth bound.

The CMJ has been related to superior performance during sprint acceleration (11) and was used as an indirect measure of vertical power. A one-dimensional force plate (Onspot©), with a sampling rate of 1,000 Hz, recorded the CMJ trials. Data from the force plate were recorded to an IBM-compatible computer via a National Instruments (DAQ-Card™-AI-16E-4) analog-to-digital converter. The subjects stood on the plate and jumped for maximal height when directed. No restrictions were placed on knee angle during the eccentric phase of the jump, and the subjects were instructed to keep their hands on their hips throughout the jump (to restrict contributions from the upper body) and maintain straight legs while they were airborne. Flight time was recorded and used to calculate jump height through the following equation: jump height = $\frac{1}{2}a(t\times\cdot 2^{-1})^2$ (a is the acceleration due to gravity [$9.8\ \mathrm{m\cdot s^{-2}}$]; t is the flight time). The use of projectile motion equations to calculate jump height has been previously adopted in the literature (11,29).

A 40-cm drop jump was used to determine reactive strength index (RSI). The RSI assesses the ability to produce force rapidly under high eccentric load. Drop jump performance has also been related to sprint performance over short distances (39), and the 40-cm height was chosen because it has been recommended as being ideal for reactive power training (3). The drop jumps were performed on the aforementioned force plate. The starting position for the drop jump involved the subject standing upright on a 40-cm box. The subjects were then instructed to keep their hands on their hips throughout the jump, and to step off (not jump off) the box with their preferred leg, which was kept consistent for all the trials. The subjects were then instructed to 'explode' up off the force plate, attempting to minimize contact time. Jump height and contact time were determined, and the RSI was calculated using the following equation: $\mathrm{RSI} = \mathrm{JH}\cdot\mathrm{CT}^{-1}$ (JH is the jump height in meters [$\frac{1}{2}at^2/2$]; CT is the length of the time in seconds the subject was in contact with the force plate after the drop) (37).

Strength Assessment

A 3RM squat was used to assess lower-body strength because it has been used previously for the assessment of strength in field sport athletes (1,9) and was conducted on a Smith machine (Life Fitness©, Artarmon, Australia). Because of the physical demands of this test, it was placed on a separate assessment day. The warm-up consisted of 15–20 body mass-only squats followed by 10 repetitions at approximately 60–70% of the subjects' estimated 1RM, which was based on their previous training experience. After a 3-minute rest interval, the subjects completed their first attempt at their 3RM. The weight was increased until the subject failed to complete 3 repetitions. No more than 5 attempts were needed before the 3RM was reached.

For the downphase of the squat, the subjects descended until the tops of their thighs were parallel to the floor. A length of non-weight–bearing wire, individually set for each subject, was tied across the Smith machine at the descent height to give the subjects an indication about the depth required for each squat (8). This was visually assessed by the researcher, and verbal cues were given to the subjects on when to halt the downphase and begin the upphase of the squat. No weightlifting belts or supportive garments were permitted. If the subject did not descend appropriately, the trial was disregarded and attempted again after the required rest period. Absolute strength was taken as the maximum load lifted for 3 repetitions. Relative strength was derived through the following equation: relative strength = $\mathrm{3RM}\cdot\text{body mass}^{-1}$.

Training Groups

After pretesting, the subjects were ranked according to 0- to 10-m velocity and randomly allocated into groups: (a) FST ($n = 9$); (b) WT ($n = 8$); (c) PT ($n = 9$); and (d) RST ($n = 9$). Because the study was designed to analyze the effects of each individual protocol, a nontraining control group was not included (22). A 6-week training program was used, because this time period has been shown to be sufficient for inducing strength, power, and speed adaptations (2,17,22). During the training period, the subjects completed their assigned sessions on 2 nonconsecutive days per week and refrained from intensive exercise in the 24 hours before each session. All the sessions were conducted at the university and supervised by the researchers.

Table 1 displays the training programs for each of the protocols. Each program was progressively overloaded. The sprint training programs (free and resisted) increased the total distance run each week. The RST group towed a load that was equivalent to 12.6% of body mass, which was determined through established methods (24). This load has been previously used in RST programs (17,37). The weights training program decreased repetitions over the course of the program to correspond with an increased load. The plyometric program increased total ground contacts per week. As previously stated, programs were matched by duration, with each session lasting approximately 60 minutes. The FST and RST groups were matched because both used the same sprint program. The weight and plyometric programs were also equated, with exercises involving bilateral (WT: squat,

TABLE 1. Programs for the FST, RST, PT, and WT groups.*

	FST and RST			PT			WT		
Wk	Interval	Sets × reps	Distance	Exercise	Sets × reps	Contacts	Exercise	Sets × reps	%1RM
1	0–5	2 × 3	30	Box jump	3 × 10	30	Squats	3 × 10–12	75
	0–10	2 × 3	60	Bounding	4 × 5	20	Step-ups	3 × 10–12	75
	0–15	1 × 3	45	Forward hop	2 × 10	20	Hip flexion	3 × 10–12	75
	0–20	1 × 3	60 (195 m)	Hurdle jump	2 × 10	20	Calf raise	3 × 10–12	75
				Drop jump	2 × 5	20 (100)			
2	0–5	2 × 4	40	Box jump	3 × 10	30	Squats	3 × 8–10	75–80
	0–10	2 × 4	80	Bounding	4 × 6	24	Step-ups	3 × 8–10	75–80
	0–15	1 × 3	45	Forward hop	3 × 8	24	Hip flexion	3 × 8–10	75–80
	0–20	1 × 3	60 (225 m)	Hurdle jump	3 × 8	24	Calf raise	3 × 8–10	75–80
				Drop jump	2 × 8	16 (118)			
3	0–5	3 × 3	45	Box jump	3 × 10	30	Squats	3 × 6	80–85
	0–10	2 × 4	80	Bounding	5 × 6	30	Step-ups	3 × 6	80–85
	0–15	1 × 4	60	Forward hop	3 × 10	30	Hip flexion	3 × 6	80–85
	0–20	1 × 3	60 (245 m)	Hurdle jump	3 × 8	24	Calf raise	3 × 6	80–85
				Drop jump	2 × 8	16 (130)			
4	0–5	3 × 3	45	Box jump	3 × 8	24	Squats	3 × 5	80–85
	0–10	3 × 3	90	Bounding	6 × 6	36	Step-ups	3 × 5	80–85
	0–15	1 × 4	60	Forward hop	3 × 10	30	Hip flexion	3 × 5	80–85
	0–20	1 × 4	80 (275 m)	Hurdle jump	3 × 10	30	Calf raise	3 × 5	80–85
				Drop jump	3 × 8	24 (144)			
5	0–5	2 × 5	50	Box jump	3 × 8	24	Squats	3 × 4	90
	0–10	2 × 5	100	Bounding	5 × 9	45	Step-ups	3 × 4	90
	0–15	1 × 4	60	Forward hop	4 × 8	32	Hip flexion	3 × 4	90
	0–20	1 × 4	80 (290 m)	Hurdle jump	4 × 8	32	Calf raise	3 × 4	90
				Drop jump	4 × 7	28 (161)			
6	0–5	3 × 4	60	Box jump	3 × 8	24	Squats	3 × 4	90
	0–10	3 × 4	120	Bounding	5 × 9	45	Step-ups	3 × 4	90
	0–15	1 × 4	60	Forward hop	5 × 8	40	Hip flexion	3 × 4	90
	0–20	1 × 4	80 (320 m)	Hurdle jump	5 × 8	40	Calf raise	3 × 4	90
				Drop jump	4 × 8	32 (181)			

*FST = free sprint training; RST = resisted sprint training; PT = plyometric training; WT = weight training; 1RM = 1 repetition maximum.

standing calf raise; PT: box jump, double-leg hurdle jump) and unilateral (WT: step-ups, cable hip flexion; PT: alternate-leg bound, single-leg forward hop) contacts. Drop jumps were also included in the plyometric program.

Statistical Analyses

All statistical analyses were computed using the Statistics Package for Social Sciences (Version 17.0). A power level of 0.8 and significance level of $p \leq 0.05$ were established. Descriptive statistics were calculated for all data and are reported as mean ± *SD*. Before training, a one-way analysis of variance determined any significant between-group differences in age, BMI, and mean pretest 0- to 10-m velocity. After training, data distribution was checked for normality with Q-Q plots. Paired-samples *t*-tests determined significant within-group changes as a result of the training. The use of paired-samples *t*-tests served to emphasize that within-group changes were the focus of this study, as opposed to between-group comparisons. Effect sizes (ESs) were calculated by the difference between the means divided by the pooled *SD*s, with 0.5–0.8 considered a medium ES and 0.8 and above a large ES (7).

RESULTS

Acceleration Kinematics

Because of reasons unrelated to the study design, 2 subjects withdrew from the WT group, leaving a total of 33 subjects (age = 23.3 ± 4.2 years; height = 1.82 ± 0.07 m; mass = 83.1 ± 8.8 kg). Despite this, there were no significant between-group differences in the BMI or pretest 0- to 10-m velocity (Table 2). Therefore, it was assumed that any changes induced over the training period could be confidently related to the applied condition.

Table 2 gives the pretest and posttest velocities for each of the training groups. Each group significantly increased the

Table 2. Change in the BMI and 0- to 5-m, 5- to 10-m, and 0- to 10-m velocity in a 10-m sprint after 6 weeks of FST, WT, PT, or RST.*†

		FST ($n = 9$)	WT ($n = 6$)	PT ($n = 9$)	RST ($n = 9$)
BMI $(\text{m}\cdot[\text{kg}^2]^{-1})$	Pre	24.78 ± 1.49	25.22 ± 2.74	24.83 ± 2.20	25.75 ± 2.71
	Post	24.87 ± 1.44	25.38 ± 2.56	24.76 ± 2.66	25.88 ± 2.47
	ES	0.06	0.06	0.03	0.05
0- to 5-m Velocity $(\text{m}\cdot\text{s}^{-1})$	Pre	3.75 ± 0.20	3.68 ± 0.13	3.78 ± 0.18	3.81 ± 0.30
	Post‡	4.01 ± 0.19	4.03 ± 0.16	3.99 ± 0.25	4.08 ± 0.26
	ES	1.33	2.40	0.96	0.96
5- to 10-m Velocity $(\text{m}\cdot\text{s}^{-1})$	Pre	6.65 ± 0.34	6.55 ± 0.11	6.62 ± 0.34	6.49 ± 0.30
	Post	6.79 ± 0.27	6.76 ± 0.18‡	6.75 ± 0.28‡	6.50 ± 0.78
	ES	0.46	1.41	0.42	0.02
0- to 10-m Velocity $(\text{m}\cdot\text{s}^{-1})$	Pre	4.81 ± 0.28	4.72 ± 0.13	4.81 ± 0.23	4.79 ± 0.31
	Post‡	5.03 ± 0.21	5.05 ± 0.14	5.01 ± 0.24	5.06 ± 0.29
	ES	0.89	2.44	0.85	0.90

*FST = free sprint training; RST = resisted sprint training; PT = plyometric training; WT = weight training; 1RM = 1 repetition maximum; ES = effect size.

†Values are mean ± *SD* and ES.

‡Significant ($p \leq 0.05$) difference between pretest and posttest.

0- to 5-m and 0- to 10-m velocity. For each of these increases, the ES were large, indicating the strength of the change. The WT and PT groups also significantly increased the 5- to 10- m velocity. The change in the 5- to 10-m velocity for the WT group had a large ES (1.41), whereas for the PT group, the ES was relatively small (0.42).

Mean step length significantly increased across all the intervals for each training group (Table 3). The strength of

Table 3. Change in SL and SF in the 0- to 5-m, 5- to 10-m, and 0- to 10-m interval in a 10-m sprint after 6 weeks of FST, WT, PT, or RST.*†

		FST ($n = 9$)	WT ($n = 6$)	PT ($n = 9$)	RST ($n = 9$)
0- to 5-m SL(m)	Pre	1.14 ± 0.08	1.15 ± 0.10	1.18 ± 0.11	1.29 ± 0.13
	Post‡	1.32 ± 0.10	1.25 ± 0.10	1.31 ± 0.12	1.39 ± 0.11
	ES	1.99	1.00	1.13	0.83
5- to 10-m SL (m)	Pre	1.60 ± 0.13	1.62 ± 0.08	1.70 ± 0.13	1.71 ± 0.11
	Post‡	1.87 ± 0.21	1.87 ± 0.19	1.81 ± 0.14	1.90 ± 0.13
	ES	1.55	1.71	0.81	1.58
0- to 10-m SL (m)	Pre	1.37 ± 0.10	1.39 ± 0.08	1.44 ± 0.11	1.50 ± 0.11
	Post‡	1.60 ± 0.14	1.56 ± 0.14	1.56 ± 0.13	1.64 ± 0.10
	ES	1.89	1.49	1.00	1.33
0- to 5-m SF (Hz)	Pre	3.32 ± 0.20	3.22 ± 0.31	3.21 ± 0.23	2.97 ± 0.36
	Post	3.04 ± 0.30‡	3.25 ± 0.29	3.07 ± 0.22	2.96 ± 0.34
	ES	1.10	0.10	0.62	0.03
5- to 10-m SF (Hz)	Pre	4.18 ± 0.29	4.05 ± 0.23	3.92 ± 0.33	3.80 ± 0.24
	Post	3.67 ± 0.41‡	3.66 ± 0.40‡	3.76 ± 0.24	3.44 ± 0.54
	ES	1.44	1.20	0.55	0.86
0- to 10-m SF (Hz)	Pre	3.52 ± 0.23	3.41 ± 0.22	3.35 ± 0.18	3.19 ± 0.26
	Post	3.17 ± 0.32‡	3.27 ± 0.31	3.22 ± 0.17‡	3.09 ± 0.29
	ES	1.26	0.52	0.74	0.36

*FST = free sprint training; RST = resisted sprint training; PT = plyometric training; WT = weight training; 1RM = 1 repetition maximum; SL = step length; SF = step frequency; ES = effect size.

†Values are mean ± *SD* and ES.

‡Significant ($p \leq 0.05$) difference between pretest and posttest.

Table 4. Change in CT and FT in the 0- to 5-m, 5- to 10-m, and 0- to 10-m interval in a 10-m sprint after 6 weeks of FST, WT, PT, or RST.*†

		FST (*n* = 9)	WT (*n* = 6)	PT (*n* = 9)	RST (*n* = 9)
0- to 5-m CT (s)	Pre	0.144 ± 0.010	0.141 ± 0.014	0.143 ± 0.010	0.157 ± 0.019
	Post	0.155 ± 0.012‡	0.145 ± 0.018	0.142 ± 0.007	0.156 ± 0.017
	ES	1.00	0.25	0.12	0.06
5- to 10-m CT (s)	Pre	0.123 ± 0.007	0.124 ± 0.011	0.122 ± 0.007	0.135 ± 0.019
	Post	0.127 ± 0.008	0.129 ± 0.019	0.122 ± 0.008	0.133 ± 0.017
	ES	0.53	0.32	0.00	0.11
0- to 10-m CT (s)	Pre	0.134 ± 0.008	0.133 ± 0.012	0.133 ± 0.007	0.146 ± 0.018
	Post	0.141 ± 0.009‡	0.137 ± 0.018	0.132 ± 0.007	0.145 ± 0.015
	ES	0.82	0.26	0.14	0.06
0- to 5-m FT (s)	Pre	0.096 ± 0.014	0.089 ± 0.007	0.094 ± 0.016	0.094 ± 0.010
	Post	0.087 ± 0.012‡	0.084 ± 0.009	0.095 ± 0.017	0.095 ± 0.011
	ES	0.69	0.62	0.06	0.10
5- to 10-m FT (s)	Pre	0.117 ± 0.016	0.118 ± 0.009	0.127 ± 0.012	0.122 ± 0.013
	Post	0.122 ± 0.020	0.112 ± 0.013	0.123 ± 0.019	0.121 ± 0.014
	ES	0.28	0.54	0.25	0.07
0- to 10-m FT (s)	Pre	0.107 ± 0.014	0.104 ± 0.007	0.111 ± 0.012	0.108 ± 0.005
	Post	0.105 ± 0.013	0.098 ± 0.010	0.109 ± 0.017	0.108 ± 0.011
	ES	0.15	0.70	0.14	0.00

*FST = free sprint training; RST = resisted sprint training; PT = plyometric training; WT = weight training; ES = effect size; CT = contact time; FT = flight time.

†Values are mean ± *SD* and ES.

‡Significant ($p \leq 0.05$) difference between pretest and posttest.

these changes is reflected in the ES for each change, with all being >1.00. The FST group significantly decreased step frequency in each interval, with ES that were all >1.00 (Table 3). The WT group significantly decreased step frequency in the 5- to 10-m interval, with an ES of 1.20. Step frequency in the 0- to 10-m interval for the PT group also significantly decreased (ES = 0.74). The RST had no significant reductions in step frequency, although the decrease in the 5- to 10-m interval had a large ES of 0.86.

Mean contact time in the 0- to 5-m and 0- to 10-m interval for the FST group significantly increased after training (Table 4). The ES associated with both these changes was

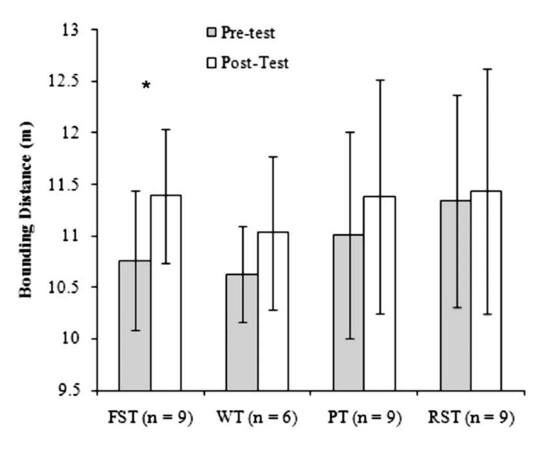

Figure 1. Change in horizontal power as measured by a 5-bound test (mean ± *SD*) after 6 weeks of free sprint (FST), weight (WT), plyometric (PT), or resisted sprint (RST) training. *Significant ($p \leq 0.05$) difference between pretest and posttest.

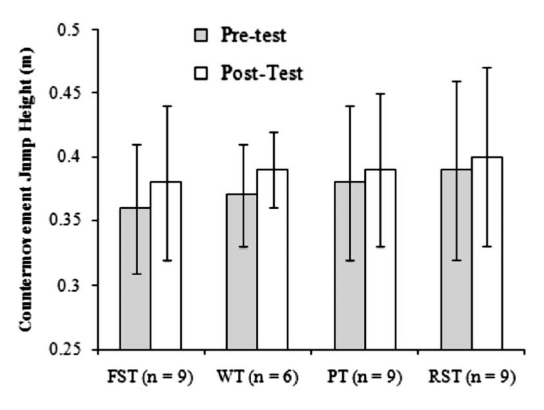

Figure 2. Change in vertical power as measured by a countermovement jump after 6 weeks of free sprint (FST), weight (WT), plyometric (PT), or resisted sprint (RST) training.

Table 5. Change in reactive power as measured by RSI, DJCT, and DJH after 6 weeks of FST, WT, PT, or RST.*†

		FST (*n* = 9)	WT (*n* = 6)	PT (*n* = 9)	RST (*n* = 9)
RSI ($JH \cdot CT^{-1}$)	Pre	1.07 ± 0.38	1.24 ± 0.21	1.31 ± 0.28	1.16 ± 0.21
	Post	1.27 ± 0.35‡	1.39 ± 0.31	1.44 ± 0.22‡	1.31 ± 0.26‡
	ES	0.55	0.57	0.52	0.63
DJCT (s)	Pre	0.298 ± 0.075	0.227 ± 0.029	0.254 ± 0.050	0.255 ± 0.017
	Post	0.251 ± 0.035	0.200 ± 0.032	0.229 ± 0.037	0.242 ± 0.025
	ES	0.80	0.88	0.57	0.61
DJH (m)	Pre	0.30 ± 0.08	0.29 ± 0.05	0.32 ± 0.06	0.28 ± 0.03
	Post	0.31 ± 0.06	0.31 ± 0.05	0.32 ± 0.04	0.27 ± 0.05
	ES	0.14	0.40	0.00	0.24

*FST = free sprint training; RST = resisted sprint training; PT = plyometrics training; WT = weights training; ES = effect size; RSI = reactive strength index ($JH \cdot CT^{-1}$); JH = jump height; CT = contact time; DJCT = drop jump contact time; DJH = drop jump height.

†Values are mean ± *SD* and ES.

‡Significant ($p \leq 0.05$) difference between pretest and posttest.

large (1.00 and 0.82, respectively). Mean 0- to 5-m flight time significantly decreased for the FST group as well (Table 4), with a medium ES of 0.69. There were no further significant changes in contact or flight time for any of the other groups. Nevertheless, the WT group did have medium ES for decreases in flight time in the 0.5- and 0- to 10-m intervals (ES = 0.62 and 0.70, respectively).

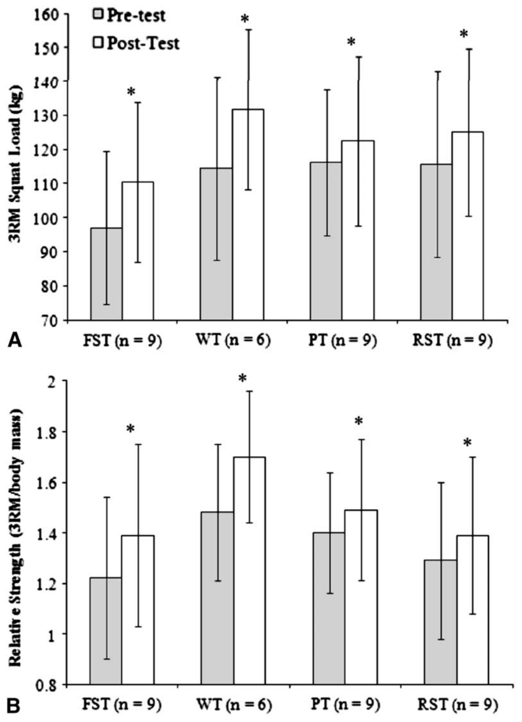

Figure 3. Change in absolute strength as measured by a 3-repetition maximum squat (3RM) (A) and relative strength derived from the 3RM squat (3RM·per body mass) (B) (mean ± *SD*) after 6 weeks of free sprint (FST), weight (WT), plyometric (PT), or resisted sprint (RST) training. *Significant ($p \leq 0.05$) difference between pretest and posttest.

Lower-Limb Power and Strength

The change in 5BT, which illustrates horizontal power, is shown in Figure 1. The FST group was the only group to significantly increase bounding distance. A large ES of 0.95 was recorded for this change. The WT group had a medium ES for the variation in 5BT from pretest to posttest (ES = 0.65), whereas the PT and RST groups both had low ES (0.35 and 0.08, respectively). No group significantly improved CMJ performance after the training intervention (Figure 2). The lack of any significant finding in changes from pretest to posttest for vertical power is also reflected in the ES for each of the groups, with all of them being relatively low (FST = 0.36; WT = 0.50; PT = 0.17; RST = 0.14).

The changes in reactive power (RSI, drop jump contact time and jump height) are shown in Table 5. The FST, PT, and RST groups significantly increased RSI after training, whereas WT did not reach significance ($p = 0.13$). The ES for all the 4 protocols were approximately 0.60, indicating a medium effect. Reactive power was further investigated by examining contact time after the drop and the subsequent jump's height. The decrease in contact time for the FST ($p = 0.07$; ES = 0.80), PT ($p = 0.06$; ES = 0.57), and WT ($p = 0.09$; ES = 0.88) groups all approached significance. Even though the change in drop jump contact time for the RST group did not approach significance ($p = 0.23$), it still had a medium ES of 0.61. In regards to jump height after the drop, there were no significant changes for any of the groups and ESs were low.

All the training groups significantly increased absolute strength (3RM squat) and relative strength (3RM·per body mass) (Figure 3). There was a medium effect for the change in absolute strength in the WT group (ES = 0.69), and a large effect for the change in relative strength (ES = 0.83). The ES for the changes in absolute and relative strength in the FST (ES = 0.58 and 0.50, respectively), PT (ES = 0.27 and 0.35, respectively), and RST (ES = 0.36 and 0.32, respectively) groups were all relatively low.

DISCUSSION

This is one of the first studies to provide specific detail regarding the adaptations that result from conducting free sprint, weights, plyometrics, and RST with the specific aim of improving sprint speed over 10 m in field sport athletes. As stated, the purpose of this study was not to compare the protocols but rather to illustrate the specific adaptations that result after their implementation. As expected, all the protocols improved sprint performance over 10 m. Analysis of specific sprint acceleration kinematics, in conjunction with measurements of lower-limb power and strength, highlight the specificity of each of the training protocols. This has significant implications for strength and conditioning professionals, who use these training modalities to enhance sport-specific performance in field and team sport athletes.

Each training group improved 0- to 5-m and 0- to 10-m velocity, and a large effect was shown for all these changes (Table 2). Previous research has shown that improvements in the 0- to 5-m interval have a strong influence upon the 10- to 15-m sprint performance (2,37). This suggests that achieving a high running velocity in the first few meters of sprinting is integral for successful acceleration during a short sprint. What must be acknowledged is that the 0- to 5-m interval featured the highest training volume for the FST and RST groups, because all sprint intervals featured this distance (i.e., every sprint had a 0- to 5-m phase). Nonetheless, developing quickness over the first few steps is essential for effective acceleration. When implemented correctly, all of the study protocols can improve short sprint speed in field sport athletes.

In the 5- to 10-m interval, only the WT and PT groups achieved significant velocity increases (Table 2). By this stage of acceleration, a field sport athlete will attain approximately 70% of their maximum velocity (14). For a field sport athlete, the distance from 5 to 10 m in a sprint could be viewed as a transitionary period between initial acceleration and peak velocity. Training protocols that encourage high force production (i.e., weights or plyometrics training) may be required to enhance performance in the transition from acceleration to maximum velocity in field sports. For example, a maximal squat can elicit a ground reaction force in excess of 5,000 N (40), whereas CMJs and drop jumps feature ground reaction forces >2,500 N (20). Our results suggest that this type of force output during training may be necessary to improve 5- to 10-m velocity. These findings highlight how essential it is for field sport athletes to incorporate certain protocols (i.e., weights and plyometrics training) into their workout regimes to elicit high external loading, which can then translate to more effective acceleration.

There were no significant changes in vertical power (i.e., CMJ) for any training group (Figure 2). Even though superior performance in a CMJ has been related to sprint performance (11), developing power in the vertical plane may not benefit acceleration because an optimal step pattern should incorporate higher horizontal and lower vertical take-off velocities (19). One of the issues with an inordinate generation of vertical power during the sprint step is a less effective gait pattern with an increased flight phase. This can then affect an athlete's dynamic balance during a match and also lead to higher ground reaction forces upon impact (26). The fact that the current training protocols did not result in significant changes to CMJ may in fact be positive for acceleration, in that any changes in power have been made specific to the sprint step action. The increased step length experienced by all the groups signifies sprint-specific gains in horizontal power (Table 3).

However, only the FST group significantly increased 5BT (Figure 1). This increase in horizontal power would likely have contributed to the significant gains in step length that were demonstrated by this group (Table 3). It was hypothesized that the FST group would be sensitive to changes in step characteristics, and this was evidenced by increases in step length. Conversely, there were also increases in contact time and decreases in step frequency (Table 3). Hunter et al. (19) established a negative interaction between step length and frequency, in that should one of these variables increase through training, there is a likelihood that the other will decrease. The change in horizontal power for the FST group, shown through the step length increases, would have contributed to the increase in mean 0- to 5-m and 0- to 10-m contact time (Table 4). This adaptation would have allowed for the force generation needed to lengthen the step. The change in contact time was balanced by a significant reduction in mean 0- to 5-m flight time (Table 4). The FST subjects may have adopted a strategy that maximized velocity by finding a balance between horizontal power generation, contact time, and flight time. These results highlight the fact that although traditional sprint training improves horizontal power and increases step length, another form of training stimulus is needed to increase step frequency in field sport athletes. This is further emphasized when considering changes to reactive power.

The FST, PT, and RST groups significantly increased RSI (Table 5). Plyometric training (25), free sprint training (25), and RST (17,37) have been previously found to improve reactive power. These protocols all involve higher movement speeds and ballistic activities that encourage rapid stretch-shortening cycle actions, whether rebounding from a sprint step or a jump. The eccentric phase of weights training tends to be slower and less ballistic in nature (32), which may partly explain the limited reactive power development for the WT group. It has to be acknowledged that the loss of 2 subjects from the WT group during the training period may have adversely affected the power to find significant changes after the WT intervention. Nonetheless, it should be highlighted that the ES for RSI was very similar for all 4 training protocols (Table 5).

Enhanced RSI was partially because of subjects becoming more efficient during ground contact. Ten weeks of sprint training or PT can reduce contact time after a drop jump (25), and similarities in push-off mechanics are a factor in the relationship between reactive strength and agility over 8-m sprints in male athletes (39). Indeed, the decrease in drop jump contact time for the FST, PT, and WT groups approached significance, whereas all the 4 protocols showed medium-to-large effect sizes (Table 5). The importance of adaptations in ground mechanics is further illustrated by the lack of significant change in jump height after the drop and its low effect sizes (Table 5).

The lack of change in jump height after the drop mirrors the results shown for the CMJ. As for the CMJ, the drop jump emphasizes vertical projection. However, during the sprint step, the power generated during support must be translated horizontally for effective transition to acceleration. The effects of this were shown primarily through step length increases for the FST, PT, and RST groups (Table 3). This is indicative of augmented intermuscular coordination, because neural adaptations have been linked to step length changes after acceleration training (22). This highlights the specificity of muscular development for the FST, PT, and RST groups, in that reactive power increased in a way that ultimately benefited acceleration. Future research could incorporate the use of electromyography to monitor adaptations from acceleration-specific resistance training, because this will provide greater information regarding neural adaptations and changes in muscular coordination.

Nonetheless, any changes to reactive power for the training groups did not translate to increases in step frequency or reductions in contact time, which are synonymous with increased movement tempo (6). For the PT group, it was hypothesized that any changes in power would also contribute to higher movement speeds as shown by enhanced step frequency and reduced contact time. However, this was not the case in this study. These results again have significant implications for strength and conditioning professionals. Training protocols such as free sprinting, plyometrics, and resisted sprinting will enhance acceleration in field sport athletes, partially through improved reactive power which will encourage increased step length. However, any attempts to further improve acceleration by increasing step frequency will require the introduction of another training stimulus (e.g., overspeed or assisted sprint training). The question of whether step length and step frequency can be developed concurrently, possibly through combining acceleration-specific resistance training with a protocol that emphasizes high-speed movements, must be investigated.

The improved acceleration for each training group was also aided by significant increases in absolute and relative strength (Figure 3). This was expected for the WT group, because appropriate strength training will improve a 3RM squat (9). The WT group experienced great gains (~15%) in absolute and relative strength, with consequent medium-to-large ES (3RM = 0.69; relative strength = 0.83). This was important for the WT group, because these subjects did not significantly improve RSI. This suggests that a different mechanism may have been used to improve acceleration. Concentric force production is essential for initial speed generation (36). The WT group's improved strength would have allowed for an increased use of concentric force to overcome inertia early in acceleration and generate a high speed, primarily through step length increases.

An improvement in reactive strength, shown by increases in RSI, could be partly responsible for the strength gains in the FST, PT, and RST groups. Improved reactive strength indicates an improved ability to attenuate eccentric loads. Jump squats integrating the concentric and eccentric phases were more effective in improving the 1RM squat in American footballers than were concentric phase-only jump squats (18). Furthermore, the plyometric program, matched by exercise with the weight program trained the same lower-limb muscle groups in a ballistic manner. When comparing ballistic squats with loads ranging from 30 to 90% of 1RM during volume-matched sets, Cronin and Crewther (10) found that the lighter load squats (30% 1RM) allowed for significantly longer time under tension for the lower-limb muscles. Additionally, because the lighter loads featured a greater number of repetitions, total force output was greater. The subjects in the PT group could have experienced the benefits of great muscle tension and a high total force output that led to increased strength. Nonetheless, the ESs recorded by the PT group for the changes in strength were low (absolute strength = 0.27; relative strength = 0.35). This would suggest that other mechanisms (i.e., improved reactive power) are more likely to be responsible for the changes in speed performance.

The strength gains made by the FST and RST groups were surprising. Regardless of the relatively low ES registered by the FST (absolute strength = 0.58; relative strength = 0.50) and RST (absolute strength = 0.36; relative strength = 0.32) groups for the changes of strength, there may be some explanations for the significant changes noted in this study. Resisted sprint training would develop strength specific to the sprint step, by increasing lower-limb force output. Lockie et al. (24) found that when towing a load equivalent to 32.2% of body mass, there was an acute increase in knee extension during acceleration in field sport athletes. This was indicative of the athlete's attempt to develop more force through a vigorous extension of the leg, which would require greater activation of the leg extensor muscle groups. If these muscle groups become stronger after RST, this would contribute to increases in 3RM seen in this study.

In relation to the strength gains made by the FST group, previous research has found that the leg muscle activation is similar for free and resisted sprint conditions (30). Any strength adaptations experienced by the RST group could conceivably be similar to that of the FST group. Improved intermuscular coordination could be a mechanism behind strength gains from FST (38). Free sprint training can increase isometric force development (25), giving this notion some merit. Another explanation may be found in the fact that the subjects did not change their normal training throughout the study, as per standards set by previous research (27,37). Because these subjects were experienced athletes participating regularly in resistance training, it is possible that training outside of the study requirements contributed to the strength changes as well. Nevertheless, the improvements shown by the WT group in sprint acceleration clearly show the importance of heavy weights training for field sport athletes.

PRACTICAL APPLICATIONS

This study has uncovered necessary information regarding specific training outcomes on sprint acceleration, power, and strength in field sport athletes. All the 4 training protocols resulted in an increase of approximately 9–10% in 0- to 5-m and 0- to 10-m velocity and increased step length. These changes in step length were the most prominent technical adaptations made after each of the training interventions. This study also revealed that the underlying mechanisms for these technique changes are protocol specific. Improvements in acceleration after FST are primarily supported by increased horizontal and reactive power. Plyometric training and RST develop reactive power, which contributes to enhanced acceleration. Weight training will cause an increase in lower-limb strength, and this improves short sprint performance. The authors recommend that specific power be developed to improve field sport acceleration. This can include enhancing the ability to generate horizontal propulsive force (FST), and improving the stretch-shortening capacity of the lower-limb muscles when rebounding from each ground contact (free sprint, plyometrics, and RST). Improving lower-limb strength via WT can also lead to step length adaptations and improved sprint acceleration, as long as the exercises used are movement-specific and progressively overloaded.

From the results of this study, strength and conditioning practitioners should note that the primary sprint acceleration kinematic adaptation from resistance training protocols in field sport athletes will be an increase in step length. Indeed, step length may be the major limiting factor for sprint performance in these athletes. None of the protocols investigated in this study caused increases in step frequency in the athletes analyzed. Future field sport acceleration research should define protocols for enhancing step frequency, and ascertaining whether combinations of training protocols (e.g., resisted sprinting combined with overspeed sprinting) can increase step length and frequency concurrently.

ACKNOWLEDGMENTS

The authors would like to acknowledge our subjects for their contribution to the study. This research project received no external financial assistance. None of the authors have any conflict of interest.

REFERENCES

1. 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: 230–235, 1999.
2. Bloomfield, J, Polman, R, O'Donoghue, P, and McNaughton, L. Effective speed and agility conditioning methodology for random intermittent dynamic type sports. *J Strength Cond Res* 21: 1093–1100, 2007.
3. Bobbert, MF, Huijing, PA, and van Ingen Schenau, GJ. Drop jumping. II. The influence of dropping height on the biomechanics of drop jumping. *Med Sci Sports Exerc* 19: 339–346, 1987.
4. Bradshaw, EJ, Maulder, PS, and Keogh, JW. Biological movement variability during the sprint start: Performance enhancement or hindrance? *Sports Biomech* 6: 246–260, 2007.
5. Bushnell, T and Hunter, I. Differences in technique between sprinters and distance runners at equal and maximal speeds. *Sports Biomech* 6: 261–268, 2007.
6. Čoh, M, Mihajloviè, S, and Praprotnik, U. Morphologic and kinematic characteristics of elite sprinters. *Acta Kinesiol Univers Tartuensis* 6(Suppl.): 100–103, 2001.
7. Cohen, J. *Statistical Power Analysis for the Behavioral Sciences* (2nd ed.). Hillsdale, NJ: Lawrence Earlbaum Associates, 1988.
8. Cotterman, ML, Darby, LA, and Skelly, WA. Comparison of muscle force production using the Smith machine and free weights for bench press and squat exercises. *J Strength Cond Res* 19: 169–176, 2005.
9. Coutts, AJ, Murphy, AJ, and Dascombe, BJ. Effect of direct supervision of a strength coach on measures of muscular strength and power in young rugby league players. *J Strength Cond Res* 18: 316–323, 2004.
10. Cronin, J and Crewther, B. Training volume and strength and power development. *J Sci Med Sport* 7: 144–155, 2004.
11. Cronin, JB and Hansen, KT. Strength and power predictors of sports speed. *J Strength Cond Res* 19: 349–357, 2005.
12. 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 Sports Exerc* 27: 1203–1209, 1995.
13. Donati, A. The association between the development of strength and speed. *New Stud Athl* 11: 51–58, 1996.
14. Duthie, GM, Pyne, DB, Marsh, DJ, and Hooper, SL. Sprint patterns in rugby union players during competition. *J Strength Cond Res* 20: 208–214, 2006.
15. Ebben, WP and Blackard, DO. Strength and conditioning practices of National Football League strength and conditioning coaches. *J Strength Cond Res* 15: 48–58, 2001.
16. Gruen, A. Fundamentals of videogrammetry–A review. *Hum Mov Sci* 16: 155–187, 1997.
17. 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.
18. Hoffman, JR, Ratamess, NA, Cooper, JJ, Kang, J, Chilakos, A, and Faigenbaum, AD. Comparison of loaded and unloaded jump squat training on strength/power performance in college football players. *J Strength Cond Res* 19: 810–815, 2005.
19. Hunter, JP, Marshall, RN, and McNair, PJ. Interaction of step length and step rate during sprint running. *Med Sci Sports Exerc* 36: 261–271, 2004.
20. Jensen, RL and Ebben, WP. Quantifying plyometric intensity via rate of force development, knee joint, and ground reaction forces. *J Strength Cond Res* 21: 763–767, 2007.
21. Kraemer, HC and Thiemann, S. *How Many Subjects? Statistical Power Analysis in Research.* Stanford, CA: Sage Publications, 1987.

22. Kristensen, GO, van den Tillar, R, and Ettema, GJC. Velocity specificity in early-phase sprint training. *J Strength Cond Res* 20: 833–837, 2006.
23. Lockie, RG, Murphy, AJ, Knight, TJ, and Janse de Jonge, XAK. Factors that differentiate acceleration ability in field sport athletes. *J Strength Cond Res*. DOI: 10.1519/JSC.0b013e31820d9f17. 25 August, 2011. Epub Ahead of Print.
24. Lockie, RG, Murphy, AJ, and Spinks, CD. Effects of resisted sled towing on sprint kinematics in field-sport athletes. *J Strength Cond Res* 17: 760–767, 2003.
25. Markovic, G, Jukic, I, Milanovic, D, and Metikos, D. Effects of sprint and plyometric training on muscle function and athletic performance. *J Strength Cond Res* 21: 543–549, 2007.
26. Mercer, JA, Devita, P, Derrick, TR, and Bates, BT. Individual effects of stride length and frequency on shock attenuation during running. *Med Sci Sports Exerc* 35: 307–313, 2003.
27. Miller, MG, Herniman, JJ, Ricard, MD, Cheatham, CC, and Michael, TJ.The effects of a 6-week plyometric training program on agility. *J Sports Sci Med* 5: 459–465, 2006.
28. Moir, G, Sanders, R, Button, C, and Glaister, M. The effect of periodized resistance training on accelerative sprint performance. *Sports Biomech* 6: 285–300, 2007.
29. Moir, G, Shastri, P, and Connaboy, C. Intersession reliability of vertical jump height in women and men. *J Strength Cond Res* 22: 1779–1784,2008.
30. Mouchbahani, R, Gollhofer, A, and Dickhuth, H. Pulley systems in sprint training. *Mod Athl Coach* 42: 14–17, 2004.
31. Murphy, AJ, Lockie, RG, and Coutts, AJ. Kinematic determinants of early acceleration in field sport athletes. *J Sports Sci Med* 2: 144–150, 2003.
32. Newton, RU, Kraemer, WJ, Häkkinen, K, Humphries, BJ, and Murphy, AJ. Kinematics, kinetics, and muscle activation during explosive upper body movements. *J Appl Biomech* 12: 31–43, 1996.
33. Rienzi, E, Drust, B, Reilly, T, Carter, JEL, and Martin, A. Investigation of anthropometric and work-rate profiles of elite South American international soccer players. *J Sports Med Phys Fitness* 40: 162–169, 2000.
34. Rimmer, E and Sleivert, G. Effects of a plyometrics intervention program on sprint performance. *J Strength Cond Res* 14: 295–301, 2000.
35. Salonikidis, K and Zafeiridis, A. The effects of plyometric, tennis-drills, and combined training on reaction, lateral and linear speed, power, and strength in novice tennis players. *J Strength Cond Res* 22: 182–191, 2008.
36. Sleivert, G and Taingahue, M. The relationship between maximal jump-squat power and sprint acceleration in athletes. *Eur J Appl Physiol Occup Phys* 91: 46–52, 2004.
37. Spinks, CD, Murphy, AJ, Spinks, WL, and Lockie, RG. Effects of resisted sprint training on acceleration performance & kinematics in Soccer, Rugby Union and Australian Football players. *J Strength Cond Res* 21: 77–85, 2007.
38. Young, WB. Transfer of strength and power training to sports performance. *Int J Sports Physiol Perf* 1: 74–83, 2006.
39. Young, WB, James, R, and Montgomery, I. Is muscle power related to running speed with changes of direction? *J Sports Med Phys Fitness* 42: 282–288, 2002.
40. Zink, AJ, Perry, AC, Robertson, BL, Roach, KE, and Signorile, JF. Peak power, ground reaction forces, and velocity during the squat exercise performed at different loads. *J Strength Cond Res* 20: 658–664, 2006.