RESEARCH NOTE

DIFFERENCES IN MUSCLE MECHANICAL PROPERTIES BETWEEN ELITE POWER AND ENDURANCE ATHLETES: A COMPARATIVE STUDY

IRINEU LOTURCO,[1] SAULO GIL,[1] CRISTIANO FROTA DE SOUZA LAURINO,[2] HAMILTON ROSCHEL,[3] RONALDO KOBAL,[1] CESAR C. CAL ABAD,[1] AND FABIO Y. NAKAMURA[4]

[1]NAR–Nucleus of High Performance in Sport, São Paulo, Brazil; [2]Department of Medical, Brazilian Track & Field Confederation, São Paulo, Brazil; [3]School of Physical Education and Sport, University of São Paulo, São Paulo, Brazil; and [4]State University of Londrina, Department of Physical Education, Londrina, Brazil

ABSTRACT

Loturco, I, Gil, S, Laurino, CFdS, Roschel, H, Kobal, R, Cal Abad, CC, and Nakamura, FY. Differences in muscle mechanical properties between elite power and endurance athletes: a comparative study. *J Strength Cond Res* 29(6): 1723–1728, 2015—The aim of this study was to compare muscle mechanical properties (using tensiomyography–TMG) and jumping performance of endurance and power athletes and to quantify the associations between TMG parameters and jumping performance indices. Forty-one high-level track and field athletes from power ($n = 22$; mean ± *SD* age, height, and weight were 27.2 ± 3.6 years; 180.2 ± 5.4 cm; and 79.4 ± 8.6 kg, respectively) and endurance (endurance runners and triathletes; $n = 19$; mean ± *SD* age, height, and weight were 27.1 ± 6.9 years; 169.6 ± 9.8 cm; 62.2 ± 13.1 kg, respectively) specialties had the mechanical properties of their rectus femoris (RF) and biceps femoris (BF) assessed by TMG. Muscle displacement (Dm), contraction time (Tc), and delay time (Td) were retained for analyses. Furthermore, they performed squat jumps (SJs), countermovement jumps (CMJs), and drop jumps to assess reactive strength index (RSI), using a contact platform. Comparisons between groups were performed using differences based on magnitudes, and associations were quantified by the Spearman's ρ correlation. Power athletes showed almost certain higher performance in all jumping performance indices when compared with endurance athletes (SJ = 44.9 ± 4.1 vs. 30.7 ± 6.8 cm; CMJ = 48.9 ± 4.5 vs. 33.6 ± 7.2 cm; RSI = 2.19 ± 0.58 vs. 0.84 ± 0.39, for power and endurance athletes, mean ± *SD*, respectively; 00/00/100, almost certain, $p \leq 0.05$), along with better contractile indices reflected by lower Dm, Tc, and Td (Tc BF = 14.3 ± 2.3 vs. 19.4 ± 3.3 milliseconds; Dm BF = 1.67 ± 1.05 vs. 4.23 ± 1.75 mm; Td BF = 16.8 ± 1.6 vs. 19.6 ± 1.3 milliseconds; Tc RF = 18.3 ± 2.8 vs. 22.9 ± 4.0 milliseconds; Dm RF = 4.98 ± 3.71 vs. 8.88 ± 3.45 mm; Td RF = 17.5 ± 1.0 vs. 20.9 ± 1.6 milliseconds, for power and endurance athletes, mean ± *SD*, respectively; 00/00/100, almost certain, $p \leq 0.05$). Moderate correlations (Spearman's ρ between −0.61 and −0.72) were found between TMG and jumping performance. The power group presented better performance in vertical jumps, supporting the validity of these tests to distinguish between endurance and power athletes. Furthermore, TMG can discriminate the "athlete-type" using noninvasive indices moderately correlated with explosive lower-body performance. In summary, both vertical jump and TMG assessments could be useful in identifying and selecting young athletes.

KEY WORDS tensiomyography, track and field, sprinters, vertical jump tests, tensiomyography, correlation

INTRODUCTION

Power and endurance athletes are thought to markedly differ in muscle fiber type composition and mechanical responses to maximal voluntary and evoked twitches. For instance, sprinters have fast fiber type dominance compared with mid/long-distance runners, favoring a powerful muscle contraction against body weight or external overloads (8). Despite the relevance of this issue, the scarcity of studies performing such comparisons is surprising (15), especially involving elite athletes. Confirming the differences in explosive power tests and quantifying their magnitude in track and field athletes performing field tests could provide the basis for discriminating specialties and possible athletes' deficiencies, especially in sprinters. It has recently been shown, for example, that performance in vertical and horizontal jump tests are highly correlated to sprinting ability in elite sprinters (17). Therefore, high-caliber sprinters are expected to jump significantly higher than endurance runners.

The maximum height reached during countermovement jumps (CMJs) has been shown to significantly differ between

---

Address correspondence to Irineu Loturco, irineu.loturco@terra.com.br.

29(6)/1723–1728

Journal of Strength and Conditioning Research

marathon runners (31.2 ± 3.1 cm), middle-distance runners (43.8 ± 4.0 cm), and sprinters (55.0 ± 5.5 cm) (29). However, because of the high responsiveness of lower limb power performance to training, even in endurance athletes (25), discriminating sprinters and endurance runners based solely on jump or power tests may lead to misclassifications.

Physical effort is required in most muscular assessment methods and, in some cases, tests are exhaustive and involve other physiological systems (e.g., the cardiovascular system) (24). Therefore, noninvasive and straightforward methods of measuring contractile properties that discriminate between contrasting phenotypes are desirable. Tensiomyography (TMG) is a valid (27) and reliable (26) method of measuring skeletal muscle mechanical properties by the simple assessment of the muscle belly radial deformation in response to an external electrical stimulus. As it has been shown to provide measures (e.g., contraction time) that are highly correlated with percentage of myosin heavy chain I (% MHC-I) (27), TMG indices are expected to be able to discriminate between athletes from different training backgrounds, such as power and endurance athletes. This measure, together with simple explosive power tests, could provide a comprehensive picture of athletes' ability to excel in endurance and sprint disciplines and help to discriminate groups more prone to perform well in each of the athleticism extremes.

Therefore, the main objectives of this study were (a) to investigate whether the muscle mechanical properties assessed by TMG are able to distinguish between endurance and power athletes and (b) to compare the outcomes produced by each one of these groups when executing 3 different types of jumps (CMJs, squat jumps (SJs), and drop jumps). Additionally, we examined the relationships between the TMG results and vertical jumping performance. According to previous investigations, we hypothesized that both jumping abilities and muscle mechanical properties would be able to discriminate power from endurance athletes. If the correlation between TMG parameters and vertical jumps were found to be positive and significant, we could advocate obtaining valuable functional information of athletes' contractile potential using nonexercise and simple measures derived from TMG.

METHODS

Experimental Approach to the Problem

This was a cross-sectional comparative and correlational study involving measures of jump performance and TMG parameters in power and endurance track and field athletes. The athletes were required to attend 2 separate testing sessions, 1 day apart. On the first day, subjects performed TMG measurements on both the rectus femoris (RF) and the biceps femoris (BF). On the second day, before performing vertical jump tests, athletes completed a 20-minute standardized warm-up, which included both general (i.e., 10-minute running at a moderate self-selected pace followed by 5 minutes of lower limb active stretching) and specific exercises (i.e., 5 minutes of squat and CMJs). All tests were conducted in the afternoon (from 16:00 to 18:00 hours). The athletes were oriented to attend the testing session in a fasting state for 2 hours, avoiding strenuous exercise and caffeine- and alcohol-containing beverages for 24 hours before the tests. Because of the strength- and power-oriented training and constant assessment routines in our sports laboratory, all athletes had been familiarized with the experimental procedures and were proficient in performing the jump tests. All jump and TMG assessments were performed by the same experienced evaluator.

Subjects

This study consisted of 41 Brazilian elite track and field athletes, divided into 2 different groups: power athletes (sprinters, jumpers, and throwers; *n* = 22) and endurance athletes (endurance runners and triathletes; *n* = 19) (Table 1). These assessments were part of a comprehensive battery of tests regularly required by the Medical Department of the Brazilian Track and Field Confederation. The sample included athletes who were Olympic, Pan-American, and National medalists, attesting to their high level of performance. Athletes were tested at the beginning of preseason, immediately after a 4-week transition phase, which occurred after an intensive competitive period. This approach avoided the possible influences of different training loads on muscle mechanical responses. All subjects were informed of the experimental risks and benefits and signed an informed consent form. Before the study, the athletes were clinically screened by the medical staff of the Brazilian Track and Field Confederation and were found to have no health problems that could affect their performance in the tests. The protocol was reviewed and approved by an institutional review board for the use of humans as experimental subjects.

Tensiomyography Assessment Protocol

Muscle displacement (Dm), contraction time (Tc), and delay time (Td) were collected for both the RF and BF muscles from the dominant leg, using a Tensiomyographer device (TMG Measurement System; TMG-BMC Ltd., Ljubljana, Slovenia). The Dm corresponds to the radial movement of the muscle belly expressed in millimeters and depends on muscle tone or stiffness. The Tc is obtained by determining

TABLE 1. Characteristics of the subjects.*

	Age (y)	Height (cm)	Weight (kg)
Power (*n* = 22)	27.2 ± 3.6	180.2 ± 5.4	79.4 ± 8.6
Endurance (*n* = 19)	27.1 ± 6.9	169.6 ± 9.8	62.2 ± 13.1

*Data are presented as mean ± *SD*.

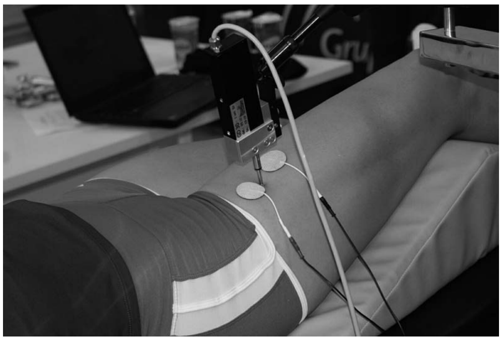

Figure 1. Tensiomyography displacement sensor placed above the rectus femoris, with the 2 electrodes used for muscle electrical stimulation.

the time lapse between Td (10% Dm) and 90% Dm. The Td is the time taken by the analyzed muscle to reach 10% of the total displacement observed (26). Rectus femoris assessments were performed with the athletes in a supine position, using a triangular wedge foam cushion to maintain the legs in a position corresponding to 120° of knee flexion. For BF assessments, the athletes were turned to the prone position, with their knees in full extension. An accurate pressure transducer (Trans-TekGK40, Panoptik d.o.o., Ljubljana, Slovenia) was positioned perpendicular to the muscle axis (Figure 1). The recording of the radial displacement took place in the muscle belly after an external electrical stimulus. To cause the twitch responses, adhesive electrodes 5/5 cm (Compex Medical AS, Ecublens, Switzerland) were connected to an electric stimulator and positioned on the muscle surface, after the arrangement of the fibers. The distance between the measurement point and the electrodes was standardized to between 55 and 60 mm. The electric pulse was set to 1 millisecond and the signal amplitude started at 30 mA. For each pulse, current amplitude was increased by 10 mA, until the maximal displacement of the muscle belly was reached. To avoid fatigue or potentiation effects, a 15-second resting period was allowed between electrical stimuli (16). The same examiner conducted all the measurements.

Vertical Jump Tests

The vertical jump tests consisted of SJs, CMJs, and drop jumps. The assessments were performed on a contact platform (Smart Jump; Fusion Sport, Coopers Plains, Australia), which gives the flight times of the subjects in milliseconds. This time is used to calculate the height of the rise of the body's center of gravity during a vertical jump ($h = g \cdot t^2 \cdot 8^{-1}$, where $g = 9.81\ m \cdot s^{-2}$). For the 3 jump tests, athletes were instructed to keep their hands on their hips. The following tests were performed: (a) SJs: the athletes were instructed to maintain a static position with a 90° knee flexion for 2 seconds before each jump attempt, without any preparatory movement, (b) CMJs: starting in a standing position, the athletes executed a downward movement followed by a rapid full extension of the lower limbs. To avoid changes in jumping coordination patterns, they freely determined the amplitude of the countermovement, and (c) Drop jumps: dropping from boxes of 45 cm, the subjects had to land with both feet at the same time and then attempting to jump as high as possible. Five attempts of each type of jump were assessed and interspersed by 15-second intervals, and the best result was considered for further analysis. During the drop jump tests, the contact time with the platform was recorded to calculate the reactive strength index (RSI), by dividing the drop jump height by the corresponding contact time. Finally, we used the ratio between the CMJs and SJs to evaluate the efficiency of the stretch-shortening cycle of power and endurance athletes (13,19).

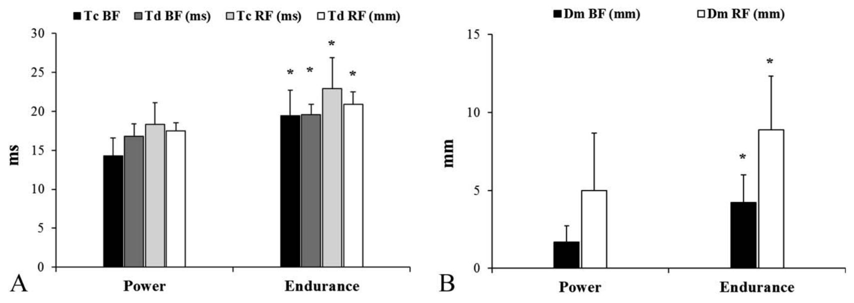

Figure 2. Contraction time (Tc), delay time (Td) (A), and displacement (Dm) (B) of the biceps femoris (BF) and Rectus femoris (RF) derived from tensiomyography in power and endurance athletes. Data are presented as mean ± *SD*. The quantitative chances were assessed qualitatively as follows: <1%, almost certainly not; 1–5%, very unlikely; 5–25%, unlikely; 25–75%, possible; 75–95%, likely; 95–99%, very likely; >99%, almost certain; *00/00/100, almost certain; ($p \leq 0.05$).

Table 2. Performance in the SJ and CMJ, the ratio between SJ and CMJ (SJ/CMJ), and the RSI in power and endurance athletes.*†

	Power	Endurance	%Chance (+/trivial/−)	Qualitative inference
SJ (cm)	44.9 ± 4.1‡	30.7 ± 6.8	100/00/00	Almost certain
CMJ (cm)	48.9 ± 4.5‡	33.6 ± 7.2	100/00/00	Almost certain
CMJ/SJ	1.09 ± 0.05	1.10 ± 0.08	12/42/43	Unclear
RSI (cm·ms^{-1})	2.19 ± 0.58‡	0.84 ± 0.39	100/00/00	Almost certain

*SJ = squat jump; CMJ = countermovement jump; RSI = reactive strength index.

†Data are presented as mean ± *SD*. The quantitative chances were assessed qualitatively as follows: <1%, almost certainly not; 1–5%, very unlikely; 5–25%, unlikely; 25–75%, possible; 75–95%, likely; 95–99%, very likely; >99%, almost certain.

‡$p \le 0.05$.

Statistical Analyses

Data are presented as mean ± *SD*. The Shapiro-Wilk test was initially used to test the normality of data. Comparisons between elite power and endurance track and field athletes were performed using the differences based on magnitudes (4). The quantitative chances of the power or endurance athletes, using a confidence interval of 90%, having better or poorer values were assessed qualitatively as follows: <1%, almost certainly not; 1–5%, very unlikely; 5–25%, unlikely; 25–75%, possible; 75–95%, likely; 95–99%, very likely; >99%, almost certain. If the chances of having better and poorer results were both >5%, the true difference was assessed as unclear (7). When data were nonnormally distributed, they were transformed by taking the natural logarithm. However, for the sake of clarity and practicality, they were presented in back-transformed values. The spreadsheet made available by Hopkins (14) was used. To quantify the association between the TMG indices and performance in vertical jump tests, Spearman's ρ correlation was used due to the distribution of data.

Results

Table 2 shows the performance of power and endurance athletes in the SJs and CMJs and the RSI. Power athletes performed better in all of them (SJs = 44.9 ± 4.1 vs. 30.7 ± 6.8 cm; CMJs = 48.9 ± 4.5 vs. 33.6 ± 7.2 cm; RSI = 2.19 ± 0.58 vs. 0.84 ± 0.39, for power and endurance athletes respectively; 00/00/100, almost certain, $p \le 0.05$). In addition, power athletes performed better in the components of RSI, namely the drop jump height (45.9 ± 5.0 vs. 33.0 ± 6.8 cm; 00/00/100, almost certain, $p \le 0.05$) and contact time (218.5 ± 49.9 vs. 431.1 ± 117.5 milliseconds; 00/00/100, almost certain, $p \le 0.05$). Results were similar when comparing endurance runners and sprinters (data not shown). Figure 2 depicts the differences in Tc and Td (A) and Dm (B) for both muscle groups (RF and BF) between power and endurance athletes (Tc BF = 14.3 ± 2.3 vs. 19.4 ± 3.3 milliseconds; Dm BF = 1.67 ± 1.05 vs. 4.23 ± 1.75 mm; Td BF = 16.8 ± 1.6 vs. 19.6 ± 1.3 milliseconds; Tc RF = 18.3 ± 2.8 vs. 22.9 ± 4.0 milliseconds; Dm RF = 4.98 ± 3.71 vs. 8.88 ± 3.45 mm; Td RF = 17.5 ± 1.0 vs. 20.9 ± 1.6 milliseconds, for power and endurance athletes respectively; 00/00/100, almost certain, $p \le 0.05$).

When pooling the power and endurance athletes' data, the Spearman's ρ correlations were moderate and significant between Tc BF ($\rho = -0.61$), Td BF ($\rho = -0.65$), Td RF ($\rho = -0.71$), and SJs (Table 2). A moderate correlation was also found between Td RF and CMJs ($\rho = -0.72$) and between Td BF ($\rho = -0.63$), Td RF ($\rho = -0.66$), and RSI. When considering only endurance runners and sprinters, similar results were obtained (data not shown).

Discussion

We hypothesized that mechanical muscle properties and vertical jumping performance would be able to discriminate power and endurance athletes. In the case of confirming the first hypothesis, a significant correlation between TMG parameters and jumping performance could exist. Findings reported herein are in accordance with our hypotheses (i.e., athlete-type discrimination ability using TMG and jump tests, and significant correlation between them). This is the first study to show these findings in elite athletes.

Vertical jump tests are widely used to train and test professional athletes (1,6). As the results are strongly associated with strength and power measures (30), it is conceivable that, in our sample of elite athletes, the power group would be able to jump significantly higher than the endurance group. This is consistent with the findings of Vuorimaa et al. (29), who reported higher countermovement jumping performance in sprinters (55.0 ± 5.5 cm) when compared with both marathon runners (31.2 ± 3.1 cm) and middle-distance runners (43.8 ± 4.0 cm), reflecting the well-known differences in muscle fiber composition (2,8), neuromechanical properties (12), and long-term training-related adaptations (9) across these athletes. Importantly, such differences in performance are commonly observed in the literature when comparing samples of power- and endurance-oriented training athletes (5,28). Within an elite group of sprinters, vertical jump is highly associated with sprinting performance (17). This result supports the relevance of assessing jump performance in this population.

Moreover, as contact time is an important factor in determining sprinting speed (22), it was expected that the power athletes, who are capable of jumping higher and generating more impulse (impulse = force × time), would present significantly higher RSI than endurance athletes. This is in line with the fact that power athletes are stronger than endurance runners, even after correcting their maximum strength of leg extensors to body mass (Loturco et al., Ph.D., February 2014, in press.). The stronger athletes studied outperformed their weaker peers in drop jump height, contact time, and RSI, thus confirming previous findings (3). Therefore, sprinters (and possibly jumpers and throwers) have to target training strategies aimed at adapting their neuromuscular system to manifest better reactive strength than athletes from other specialties in track and field, such as middle- and long-distance runners. Nevertheless, endurance athletes should not neglect neuromuscular development leading to increased explosive power because of its contribution to enhanced running economy and time-trial performance (23).

Finally, the absence of differences in the CMJs and SJs ratio between the power and endurance groups might be due to the elite level of the athletes (13,19). It is important to emphasize that our sample comprised national and international competitors and, even in the group of endurance athletes, the efficiency of the stretch-shortening cycle is crucial to sports performance because of the aforementioned factors. Nowadays, most coaches and athletes are aware of the effectiveness of concurrent endurance and explosive type strength training on neuromuscular and endurance performance (21). For instance, in a study by Ramirez-Campillo et al. (25), highly competitive middle- and long-distance runners improved their 2.4-km time trial, sprinting ability and performance in CMJs and drop jumps after explosive type training, although the control group did not demonstrate any improvement. Therefore, depending on the training methods adopted, endurance runners are able to present similar CMJ and SJ ratios compared with power athletes, regardless of lower vertical jumping performance in isolation.

The differences in the muscle fiber type composition between power and endurance athletes have been reported (2,8). As Simunic et al. (27) found significant correlations between muscle mechanical parameters and muscle fiber type composition, the differences in Tc, Td, and Dm between power and endurance athletes reported in this study were consistent with our expectations. Moreover, this study confirms the validity of TMG in discriminating groups of athletes at the extremes of human performance (i.e., sprint and endurance). Rey et al. (26) have previously shown this capability of discriminating athletes. Despite soccer players being more homogeneous in physical terms compared with track and field athletes, Tc was greater in external defenders than central defenders and goalkeepers for RF. This is possibly linked to the positional roles of central defenders and goalkeepers, who are required to jump and dive to a greater extent than central defenders. Recently, TMG was shown to be sensitive enough to discriminate sex and lateral symmetry in top-level kayakers (10) and track adaptations over the course of a season in road cyclists (11). Curiously, both power (18.3 ± 2.8 milliseconds) and endurance groups (22.9 ± 4.0 milliseconds) in this study presented faster Tc of RF than the road cyclists (35.5–46.7 milliseconds). This means that the contractile properties of track and field athletes are phenotypically faster than those found in road cyclists, despite endurance runners (8.88 mm) resembling the Dm of cyclists (7.4–8.8 mm), implying similar muscle tone and tendon stiffness. The Tc of athletes in our sample was also shorter than those found in soccer players (25.80–31.52 milliseconds), while soccer players presented slightly higher Dm (10.82–11.72 mm). Finally, Td RF (17.5 ± 1.0 and 20.9 ± 1.6 milliseconds in power and endurance athletes, respectively) were shorter in our athletes than in soccer players (24.22–26.55 milliseconds), suggesting that muscle activation time is optimized in both power and endurance track and field athletes.

To the best of our knowledge, this is the first investigation to observe significant correlations between muscle mechanical responses and vertical jumping ability in elite athletes. This is contrary to our previous (unpublished) observations in soccer players. It is possible that the wide range of technical and physical characteristics that determine success in team-sports affect performance in specific assessments, including the vertical jump tests. Also, soccer players are more likely to be "mixed" in terms of fiber type composition (20), compared with track and field athletes. Consequently, the TMG parameters may not be strongly associated with jumping performance in team sport athletes. However, the "natural and specific talent" of track and field endurance and/or power athletes is capable of producing consistent outcomes in these tests, more strongly related to their endowments and specific training history (18), increasing the values of associations with the neuromechanical characteristics evaluated by TMG parameters.

PRACTICAL APPLICATIONS

The findings demonstrate that power athletes are able to perform better than endurance athletes in vertical jumping tests and in the components of the RSI (i.e., drop jump height and contact time) supporting the use of these tests to discriminate between athletes more prone to excel in the extremes of human performance (endurance and power athletes). Furthermore, these results suggest that the muscle mechanical properties assessed by TMG could provide important information regarding the athlete-type discrimination, especially in modalities that involve power and endurance abilities, such as track and field sports. The combination of TMG and explosive testing can help professionals to screen the functional abilities and physical characteristics of their athletes. Finally, the relationships between muscle mechanical properties and other performance measures (i.e., sprinting speed and changing-of-direction ability), and the potential to identify talents among young and prospective athletes must be further investigated.

REFERENCES

1. Adams, K, O'Shea, KL, and Climstein, M. The effects of six weeks of squat, plyometric, and squat-plyometric training on power production. *J Appl Sports Sci Res* 6: 36–41, 1992.
2. Baguet, A, Everaert, I, Hespel, P, Petrovic, M, Achten, E, and Derave, W. A new method for non-invasive estimation of human muscle fiber type composition. *PLoS One* 6: e21956, 2011.
3. Barr, MJ and Nolte, VW. The importance of maximal leg strength for female athletes when performing drop jumps. *J Strength Cond Res* 28: 373–380, 2014.
4. Batterham, AM and Hopkins, WG. Making meaningful inferences about magnitudes. *Int J Sports Physiol Perform* 1: 50–57, 2006.
5. Boullosa, DA, Tuimil, JL, Alegre, LM, Iglesias, E, and Lusquinos, F. Concurrent fatigue and potentiation in endurance athletes. *Int J Sports Physiol Perform* 6: 82–93, 2011.
6. Buchheit, M, Mendez-Villanueva, A, Delhomel, G, Brughelli, M, and Ahmaidi, S. Improving repeated sprint ability in young elite soccer players: Repeated shuttle sprints vs. explosive strength training. *J Strength Cond Res* 24: 2715–2722, 2010.
7. Buchheit, M, Spencer, M, and Ahmaidi, S. Reliability, usefulness, and validity of a repeated sprint and jump ability test. *Int J Sports Physiol Perform* 5: 3–17, 2010.
8. Costill, DL, Daniels, J, Evans, W, Fink, W, Krahenbuhl, G, and Saltin, B. Skeletal muscle enzymes and fiber composition in male and female track athletes. *J Appl Physiol* 40: 149–154, 1976.
9. de Villarreal, ES, Gonzalez-Badillo, JJ, and Izquierdo, M. Low and moderate plyometric training frequency produces greater jumping and sprinting gains compared with high frequency. *J Strength Cond Res* 22: 715–725, 2008.
10. García-García, O, Cancela-Carral, JM, and Huelin-Trillo, F. Neuromuscular profile of top level women kayakers, assessed through tensiomyography. *J Strength Cond Res* 29: 844–853, 2014.
11. Garcia-Garcia, O, Cancela-Carral, JM, Martinez-Trigo, R, and Serrano-Gomez, V. Differences in the contractile properties of the knee extensor and flexor muscles in professional road cyclists during the season. *J Strength Cond Res* 27: 2760–2767, 2013.
12. Hakkinen, K, Mero, A, and Kauhanen, H. Specificity of endurance, sprint and strength training on physical performance capacity in young athletes. *J Sports Med Phys Fitness* 29: 27–35, 1989.
13. Harrison, AJ, Keane, SP, and Coglan, J. Force-velocity relationship and stretch-shortening cycle function in sprint and endurance athletes. *J Strength Cond Res* 18: 473–479, 2004.
14. Hopkins, WG. How to interpret changes in an athletic performance test. *Sportsci* 8: 1–7, 2004.
15. Hudgins, B, Scharfenberg, J, Triplett, NT, and McBride, JM. Relationship between jumping ability and running performance in events of varying distance. *J Strength Cond Res* 27: 563–567, 2013.
16. Krizaj, D, Simunic, B, and Zagar, T. Short-term repeatability of parameters extracted from radial displacement of muscle belly. *J Electromyogr Kinesiol* 18: 645–651, 2008.
17. Loturco, I, D'Angelo, RA, Fernandes, V, Gil, S, Kobal, R, Abad, CCC, Kitamura, K, and Nakamura, FY. Relationship between sprint ability and loaded/unloaded jump tests in elite sprinters. *J Strength Cond Res* 29: 758–764, 2014.
18. Malina, RM. Physical growth and biological maturation of young athletes. *Exerc Sport Sci Rev* 22: 389–433, 1994.
19. McGuigan, MR, Doyle, TL, Newton, M, Edwards, DJ, Nimphius, S, and Newton, RU. Eccentric utilization ratio: Effect of sport and phase of training. *J Strength Cond Res* 20: 992–995, 2006.
20. Metaxas, TI, Mandroukas, A, Vamvakoudis, E, Kotoglou, K, Ekblom, B, and Mandroukas, K. Muscle fiber characteristics, satellite cells and soccer performance in young athletes. *J Sports Sci Med* 13: 493–501, 2014.
21. Mikkola, JS, Rusko, HK, Nummela, AT, Paavolainen, LM, and Hakkinen, K. Concurrent endurance and explosive type strength training increases activation and fast force production of leg extensor muscles in endurance athletes. *J Strength Cond Res* 21: 613–620, 2007.
22. Morin, JB, Edouard, P, and Samozino, P. Technical ability of force application as a determinant factor of sprint performance. *Med Sci Sports Exerc* 43: 1680–1688, 2011.
23. Paavolainen, L, Hakkinen, K, Hamalainen, I, Nummela, A, and Rusko, H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J Appl Physiol (1985)* 86: 1527–1533, 1999.
24. Paavolainen, L, Hakkinen, K, Nummela, A, and Rusko, H. Neuromuscular characteristics and fatigue in endurance and sprint athletes during a new anaerobic power test. *Eur J Appl Physiol Occup Physiol* 69: 119–126, 1994.
25. Ramirez-Campillo, R, Alvarez, C, Henriquez-Olguin, C, Baez, EB, Martinez, C, Andrade, DC, and Izquierdo, M. Effects of plyometric training on endurance and explosive strength performance in competitive middle- and long-distance runners. *J Strength Cond Res* 28: 97–104, 2014.
26. Rey, E, Lago-Penas, C, and Lago-Ballesteros, J. Tensiomyography of selected lower-limb muscles in professional soccer players. *J Electromyogr Kinesiol* 22: 866–872, 2012.
27. Simunic, B, Degens, H, Rittweger, J, Narici, M, Mekjavic, IB, and Pisot, R. Noninvasive estimation of myosin heavy chain composition in human skeletal muscle. *Med Sci Sports Exerc* 43: 1619–1625, 2011.
28. Ugrinowitsch, C, Tricoli, V, Rodacki, AL, Batista, M, and Ricard, MD. Influence of training background on jumping height. *J Strength Cond Res* 21: 848–852, 2007.
29. Vuorimaa, T, Hakkinen, K, Vahasoyrinki, P, and Rusko, H. Comparison of three maximal anaerobic running test protocols in marathon runners, middle-distance runners and sprinters. *Int J Sports Med* 2(Suppl.17): S109–S113, 1996.
30. 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.