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ORIGINAL RESEARCH

PREDICTIVE FACTORS OF ELITE SPRINT PERFORMANCE: INFLUENCES OF MUSCLE MECHANICAL PROPERTIES AND FUNCTIONAL PARAMETERS

Running head: Predictive factors of sprint performance

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ABSTRACT

Sprint performance relies on many different mechanical and physiological factors. The purpose of this study was to identify, among a variety of strength-power exercises and tensiomyography parameters, the best predictors of maximum running speed in elite sprinters and jumpers. To test these relationships, nineteen power track and field athletes, 4 long jumpers and 15 sprinters (men: 12; 22.3 ± 2.4 years; 75.5 ± 8.3 kg; 176.5 ± 5.6 cm; women: 7; 23.8 ± 4.2 years; 56.9 ± 5.4 kg; 167.4 ± 5.8 cm) were assessed using different intensities of tensiomyography derived velocity of contraction (Vc), squat and countermovement jumps, drop jump at 45 and 75 cm; and a 60-m sprint time. In addition, the mean propulsive power (MPP) and peak power (PP) outputs were collected in the jump squat (JS) and half squat exercises (HS). Based on the calculations of the Vc at 40 mA, the athletes were divided (by median split analysis) into two groups: higher and lower Vc 40 mA groups. The magnitude based-inference method was used to compare the differences between groups. The correlations between mechanical and functional measures were determined using the Pearson's test. A multiple regression analysis was performed to predict sprint performance, using the Vc at 40 mA, jump heights, and JS and HS power outputs as independent variables. The higher Vc 40 mA group demonstrated *likely* better performances than the lower Vc 40 mA group in all tested variables. Large to nearly perfect significant correlations were found between sprint time, jump heights, and power outputs in both JS and HS exercises. Notably, the Vc 40 mA associated with the vertical jump height and MPP in JS explained > 70% of the shared variance in sprint times. In conclusion, it was found that faster athletes performed better in strength-power tests, in both loaded and unloaded conditions, as confirmed by the strong correlations observed between speed and power

measures. Lastly, the Vc also showed a marked selective influence on sprint and power capacities. These findings reinforce the notion that maximum running speed is a very complex physical capacity, which should be assessed and trained using several methods and training strategies.

Keywords: acceleration, power output, Olympic athletes, top-speed, muscle mechanical properties

INTRODUCTION

Maximum sprint performance is a multifactorial phenomenon which depends on many interrelated factors, such as rate of force development, muscle power, maximum dynamic strength and anaerobic power (21, 56). Due to the importance of acceleration and speed in multiple sports, several studies have been conducted to identify the main predictors of these complex physical capacities. More recently, the ability to apply the resultant force vector with a forward orientation throughout the acceleration phase of sprinting (i.e., velocity-oriented force-velocity profile) has been shown to be a crucial (and perhaps the most important) determinant of 100-m performance (62, 63). In this context, it appears that the orientation of the force applied onto the ground while sprinting is more important than its magnitude to achieve higher speeds (63).

Apart from the descriptive research on its mechanical aspects, there is extensive literature examining the effects of different types of exercises and training strategies on sprint and acceleration performance (16, 53). Accordingly, Contreras et al. (16) demonstrated that a horizontally oriented movement (i.e., hip thrust) is superior to the front squat in enhancing short-sprint capacity (i.e., 10- and 20-m). In contrast, vertically oriented exercises (i.e., vertical jumps) seem to have better transference to the top-speed phases, which is likely related to the increased role of vertical peak forces at higher running velocities (53, 81). In addition to exercise-type, the movement velocity (as defined by the load) might play a critical role in improving high-velocity performance capabilities. For instance, in a short-term study (i.e., 8 weeks), it was detected that light-loads (30% of 1 repetition maximum [1RM]) moved as quickly as possible show an overall trend of increasing speed-related abilities, whereas heavy-load training (80% 1RM) results in negligible influences on these variables (60). The same does not hold true for interventions aiming to acutely improve sprint times (i.e., postactivation potentiation effects), which seem to be more positively influenced by a bout of "low-volume heavy lifting" than by a bout of "low-volume light lifting" (i.e., 1 set of 3 repetitions of squats at 90% 1RM or loaded jumps at 30% 1RM, respectively) (59).

Numerous cross-sectional analyses have also been conducted to identify the best predictors of maximum sprint capacity (21, 35, 49, 83). Despite their recognized limitations (i.e., impossibility of establishing a causal relationship) (21), association studies are particularly useful in top-level sports, where prospective designs are intrinsically limited by feasibility issues, such as small sample sizes, congested fixture schedules, and the necessity to adopt individualized training plans (3, 11, 57). For example, in a comprehensive investigation comprising various isoinertial and isokinetic strength-power assessments, the vertical jump outputs (squat and countermovement jump heights, and relative power in loaded jump squat [W/kg]) were the only variables significantly related to acceleration and speed performance (21). Similarly, Loturco et al. (49) observed strong correlations (r ~ 0.83) between vertical and horizontal jumps and competitive performance in 100-m dash events. From these data, it is possible to infer that both loaded and unloaded jumps may be equally used to improve and monitor peak sprinting performance in highly trained subjects.

Another possible and practical way to analyze the speed-power profile of elite athletes is through the examination of their muscle mechanical parameters (22, 75). In this sense, the implementation of non-invasive approaches able to rapidly provide functional and accurate information on athletes' contractile potential is of great interest for coaches and sport scientists. In the last decade, a new method called tensiomyography (TMG) has been increasingly used by many researchers for such purpose (74, 75, 78). TMG is a valid and reliable technique for assessing muscle function, through the simple measurement of the muscle belly radial deformation in response to an electrical stimulus (69, 74). Indeed, the mechanical responses of skeletal muscles have been shown to be sensitive discriminators of "athlete-type", with more powerful individuals demonstrating greater levels of stiffness and faster contraction times than their weaker counterparts (46). To draw these conclusions, researchers usually consider two measures with great stability, automatically provided by the TMG system: muscle displacement (Dm) and contraction time (Tc) (34, 74). Nonetheless, it has been noted that these primary mechanical parameters (i.e., time and distance) present distinct responses to chronic training (23, 51), which could preclude a precise diagnosis of muscle functionality. Consequently, in top-level sports, some authors have been suggesting the use of a more integrated TMG outcome, capable of simultaneously combining in its calculation both time- and distance-related variables (i.e., velocity of contraction [Vc]) (51). In fact, the Vc seems to be a suitable indicator of muscle function, while also demonstrating a marked capacity to detect the specific adaptations induced by a given training period (51). Nevertheless, the ability of this novel and sensitive TMG measurement to predict physical performance remains to be established.

The possibility of better understanding and defining the neuromechanical aspects most related to maximum speed capacity in individuals at the extreme of human performance (e.g., Olympic athletes) may help coaches and sport scientists to develop more effective and suitable training strategies. Moreover, the opportunity to integrate various neuromuscular tests and noninvasive muscle assessments provided by TMG into the same research opens new perspectives in the field of sport science, especially with respect to top-level sports. Thus, the main objective of this study was to identify, among a variety of strength-power exercises and intensities of Vc, the best predictors of sprinting speed in elite sprinters and jumpers. Given the importance of relative power production and muscle contractile properties for sprint performance (21, 46, 51, 62), we hypothesized that greater running speeds would be associated with higher power outputs and increased contraction velocities.

METHODS

Experimental approach to the problem

This cross-sectional descriptive study aimed to identify the best predictors of sprinting velocity using different functional and mechanical parameters. To define these predictors, power track & field athletes performed the tests, on the same day, in the following order: 1) TMG in the dominant leg; 2) vertical jumps comprising squat, countermovement, and drop jumps (SJ, CMJ, and DJ, respectively); 3) a 60-m sprint; and 4) jump squat (JS) and half-squat exercises (HS) assessing mean propulsive and peak power outputs (MPP and PP, respectively). Between each test a 15-min interval was implemented to explain the next testing procedures and adjust the devices. All physical tests were performed between 9:00 a.m. and 13:00 p.m.

Subjects

Nineteen elite power track & field athletes, 4 long jumpers and 15 sprinters (men: 12; 22.3 ± 2.4 years; 75.5 ± 8.3 kg; 176.5 ± 5.6 cm; women: 7; 23.8 ± 4.2 years; 56.9 ± 5.4 kg; 167.4 ± 5.8 cm) participated in this study. The sample comprised 3 athletes who participated in the last Olympic Games (Rio-2016), while the other participants have been involved in Pan-American and South-American competitions, attesting their high level of competitiveness. A standardized warm-up was performed after the TMG assessments, comprising moderate to light self-selected runs for 5-min, and sub-maximal attempts of each test were also performed prior to the maximal tests. To perform the tests, athletes arrived at the sports laboratory prior to the first training session of the week in a fasting state for at least 2-h (1), avoiding alcohol and caffeine consumption for at least 24-h before the tests. All athletes had been previously familiarized with the testing procedures due to their constant assessments in our facilities. Prior to participating in this study, athletes were briefed on the experimental design and signed an informed consent form. The study was approved by the local Ethics Committee.

Tensiomyography assessment

The Vc was recorded from both the rectus femoris (RF) and biceps femoris (BF) muscles from the dominant leg (69), using a TMG device (TMG Measurement System, TMG-BMC Ltd., Ljubljana, Slovenia). The TMG-derived Vc was calculated by dividing the Dm by the sum of the Tc and the delayed time (Td) (51). The RF measurement was performed with the athletes in a supine position, using a triangular wedge foam cushion to maintain the legs in a position corresponding to 120^{o} of knee flexion. The sensor was placed at 50% of the line from the anterior superior iliac spine to the superior part of the patella. For BF measurement, the athletes adopted a prone position, with their knees in full extension. The sensor was placed at 50% of the line between the ischial tuberosity and lateral epicondyle of the tibia. An accurate pressure transducer (Trans-TekwGK40, Ljubljana, Slovenia) was positioned perpendicular to the muscle axis. The recording of the radial displacement took place in the muscle belly after an external electrical stimulus. To induce 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, following 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 $m.s^{-1}$ and the signal amplitude started at 40 mA. For each pulse, current amplitude was increased by 20 mA until 100 mA and finished with the maximal electric stimulus available (110 mA). The Vc from each muscle tested at all electric intensities and the maximum Vc value were retained for data analysis purposes. To avoid fatigue or potentiation effects, a 15-s rest period was allowed between electrical stimuli (39). The same experienced testing assessor conducted all the measurements.

Vertical Jumps

Vertical jump height was assessed using SJ, CMJ, and DJ from a 45- and 75-cm high box. In the SJ, athletes were required to remain in a static position with a 90° knee flexion angle for ~ 2-s before jumping, without any preparatory movement. In the CMJ, athletes were instructed to execute a downward movement followed by complete extension of the legs and were free to determine the countermovement amplitude to avoid changes in jumping coordination. In the DJ, participants were instructed to leave the box with knees and ankles fully extended and land in a similarly extended position to ensure the validity of the test. All jumps were executed with the hands on the hips and the athletes were instructed to jump as high as possible. The jumps were performed on a contact platform (Elite Jump®, S2 Sports, São Paulo, Brazil). A total of five attempts were allowed for each jump, interspersed by 15-s intervals. The best attempts for the SJ and CMJ were used for the analyses. In addition, the eccentric utilization ratio (EUR) was obtained from the SJ and CMJ performances, following the procedures described by McGuigan et al. (61). For the DJ, the reactive strength index (RSI) was taken from the jump height divided by the ground contact time (CT) before the take-off. The DJ heights (45- and 75-cm) were selected due to their established ability to determine optimal RSI and predict sprinting speed (5, 65). The best RSI and respective DJ height and CT were used for data analysis.

Sprinting time

Five pairs of photocells (Smart Speed, Fusion Equipment, Brisbane, AUS) were positioned at distances of 0, 10-, 20-, 40-, and 60-m along the sprinting course. Athletes sprinted twice, starting from a standing position 0.3-m behind the starting line. To avoid weather influences, the sprint tests were performed on an indoor running track. An 8-min rest interval, chosen in accordance with the athletes' technical staff and based on previous studies using all-out sprint tests (41, 64, 82, 84), was allowed between the two attempts and the fastest time was considered for the analyses. Athletes performed the sprinting tests wearing their own cleats.

Bar mean propulsive and peak power outputs

Bar power outputs (MPP and PP) were measured in the JS and HS exercises; all performed on a Smith-Machine (Hammer Strength Equipment, Rosemont, IL, USA). The athletes were instructed to execute three repetitions at maximal velocity for each load, with a 5-min interval provided between sets. The test started at a load corresponding to 40% of the individual body mass (BM) (46). For both JS and HS, a load of 10% of BM was gradually added in each set until a clear decrement in the MPP or the PP was observed (all assessments exhibited a parabolic-shaped curve and all athletes reached their maximum power production in both JS and HS exercises). In the JS, the athletes executed a knee flexion in a controlled form, until the thigh was parallel to the ground, which was visually inspected by an experienced testing conductor and, after a verbal command, jumped as fast as possible without their shoulder losing contact with the barbell. The HS was executed in a similar fashion to the JS, except that the subjects were instructed to move the bar as fast as possible without losing foot contact with the ground. The displacement of the bar was checked during all repetitions to guarantee the consistency of the eccentric action across the attempts. To determine power outputs, a linear transducer (T-Force, Dynamic Measurement System; Ergotech Consulting S.L., Murcia, Spain) was attached to the Smith-Machine bar. The bar position data were sampled at 1,000 Hz using a computer. The finite differentiation technique was used to calculate bar velocity and acceleration. The maximum MPP and PP obtained in each exercise, both divided by the athletes' BM, were used for analysis purposes.

Statistical analyses

Data are presented as means ± standard deviation. Data normality was tested using the Shapiro-Wilk test. The athletes were divided, using a median split analysis, into two groups according to their Vc 40 mA outcomes (higher and lower Vc 40 mA groups). To compare the results of the assessments performed between male and female athletes and between higher and lower Vc 40 mA groups, the magnitude based-inference method was used (6). The quantitative chances of finding differences in the variables tested were assessed qualitatively as follows: <1%, almost certainly not; 1% to 5%, very unlikely; 5% to 25%, unlikely; 25% to 75%, possible; 75% to 95%, likely; 95% to 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. The magnitudes of the differences in the variables tested were expressed as standardized mean differences (Cohen's *d*) and their respective confidence limits (CL) (13). Threshold values for Cohen's *d* statistics were: <0.2, trivial; 0.2-0.6, small; 0.6-1.2, moderate; 1.2-2.0, large; 2.0-4.0, very large and; >4.0, nearly perfect (30). In addition, Pearson product-moment coefficient of correlation was used to analyze the relationships between the performances in the 60-m (and its shorter split distances; 10-, 20- 40-m) sprinting time with the vertical jump outcomes, the MPP and PP in the JS and HS exercises, and the differences in the vertical jump height between SJ and CMJ, as well as the differences in the MPP and PP outputs between JS and HS exercises. Correlations between the performance tests (sprinting time, vertical jumps, and power outputs in JS and HS exercises) and the TMG-derived Vc in the RF and BF muscles for the different intensities of electrical stimulus were also tested. The threshold used to qualitatively assess the correlations was based on the following criteria: <0.1, trivial; 0.1-0.3, small; 0.3-0.5, moderate; 0.5-0.7, large; 0.7-0.9, very large; >0.9 nearly perfect (30). A multiple regression analysis was performed to predict the 60-m sprint performance, using as independent variables the Vc 40 mA, the vertical jumping heights, and the JS and HS power outputs. The possibility of collinearity between the predictive variables in the multiple regression models was examined using the variance inflation factor (VIF) and tolerance (i.e., VIF < 10 and tolerance > 0.2) (25, 36, 77). Finally, intraclass correlation coefficients (ICCs) were used to indicate the relationship within vertical jumps (loaded and unloaded conditions) and HS for height, peak power, and mean propulsive power. The ICC was 0.93 for the loaded SJ and 0.95 for the HS (on average, for both PP and MPP); 0.96 for the SJ, and 0.94 for the CMJ and DJ. The significance level was set as $P < 0.05$.

RESULTS

All data presented normal distribution. The VIF and tolerance values did not overtake the thresholds previously established, attesting that the independent variables (i.e., Vc 40 mA, jump heights, and power outputs) were not collinear. Since the correlational analysis demonstrated similar outcomes for male and female athletes (i.e., correlation values within the same qualitative threshold), they were presented together to facilitate visualization and interpretation.

The comparisons of the sprinting time, vertical jumps, and power outputs in the JS and HS exercises between male and female athletes are presented in table 1. The difference in the EUR between male and female athletes was rated as *unclear* (male: 5.37 ± 3.52%, female: 6.73 ± 3.50%; % of chances: 65/23/12; ES [90% CL] = 0.38 [-0.45; 1.21]). The absolute values of the power outputs (MPP and PP) in the JS and HS exercises were *almost certainly* higher in male when compared to female power track & field athletes (MPP JS: male: 1197.9 ± 169.1 W; female: 662.5 ± 100.0 W; ES [90%

CL]: 3.69 [2.93; 4.46]; PP JS: male: 2706.8 ± 409.4 W; female: 1676.5 ± 205.9 W; ES [90% CL]: 3.03 [2.27; 3.78]; MPP HS: male: 868.0 ± 131.5 W; female: 511.5 ± 77.8 W; ES [90% CL]: 3.15 [2.29; 4.00]; PP HS: male: 2065.1 ± 341.8 W; female: 1221.3 ± 235.5 W; ES [90% CL]: 2.76 [1.88; 3.65]). Table 2 shows the TMG-derived Vc for the RF and BF muscles at the different intensities of electrical stimulus comparing male and female athletes.

*****INSERT TABLE 1 HERE*****

*****INSERT TABLE 2 HERE*****

The correlation between 60-m sprinting time and vertical jump outcomes is presented in table 3. The correlation between 60-m sprinting time and the vertical jumps with the power outputs (MPP and PP) in the JS and HS exercises is demonstrated in table 4. The correlation (*r*) between 60-m sprinting time and absolute power outputs in the JS and HS exercises were -0.51, -0.49, -0.52, and -0.54, for 10-m; -0.69, -0.69, -0.52, and -0.58, for 20-m; -0.67, -0.67, -0.51, and -0.60, for 40-m; and -0.69, -0.69, -0.53, and -0.63, for 60-m with MPP and PP in the JS and HS exercises, respectively ($P <$ 0.05, for all correlations).

*****INSERT TABLE 3 HERE*****

*****INSERT TABLE 4 HERE*****

Table 5 depicts the correlation between 60-m sprinting time and the differences in jump height between CMJ and SJ, and the differences in the power outputs (MPP and PP) between JS and HS exercises. The correlation between Vc in the RF and BF muscles and sprinting time, vertical jumps, and the power outputs in the JS and HS exercises are demonstrated in table 6.

*****INSERT TABLE 5 HERE*****

*****INSERT TABLE 6 HERE*****

Figure 1 depicts the standardized differences between higher and lower Vc 40 mA groups for the SJ and CMJ heights, MPP and PP in the JS exercise, and sprint times in 40- and 60-m. The higher Vc 40 mA group demonstrated *likely* better performances than the lower Vc 40 mA group in the aforementioned variables. The comparisons between higher and lower Vc 40 mA groups for the following variables tested (DJ outcomes, sprint time in 10- and 20-m, and power outputs in the HS exercise) were all rated as *unclear* (ES varying from 0.08 to 0.47). Table 7 presents the predictions (R^2) of the sprinting time in the different distances using a multiple regression analysis combining the Vc at 40 mA with the vertical jump heights and power outputs in the JS and HS exercises as independent variables.

*****INSERT FIGURE 1 HERE*****

*****INSERT TABLE 7 HERE*****

DISCUSSION

From a general perspective, the results presented here corroborate our previous hypothesis since the faster athletes performed better in strength-power assessments, in both loaded and unloaded conditions, as indicated by the strong correlations observed between speed and power measures. Furthermore, the Vc also showed a selective influence on sprint and power capacities, given that the higher Vc 40 mA group demonstrated *likely* better performances (than the lower Vc 40 mA group) in SJ, CMJ, MPP JS, PP JS, 40-m, and 60-m. This is the first study to report that the maximum speed ability of elite sprinters and jumpers can be significantly related to their respective performances in power tests and muscle mechanical measurements (i.e., Vc).

As aforementioned, the strong associations between speed and power measures have been extensively reported in the literature (21, 49, 83). Indeed, the ability to produce high forces at high velocities (i.e., maximal power production) plays a key role in sprint performance (14, 73). Further, it seems that these relationships are significantly strengthened when the absolute values of muscle power are normalized by the subjects' body mass (i.e., relative power) (4, 21). Our data are in line with these observations indicating that, when compared to absolute power values (i.e., MPP and PP), MPP_{REL} and PP_{REL} (assessed in JS or HS exercises) can better predict maximum running speeds. Based on previous studies, it is reasonable to assume that these relative parameters tend to be more associated with maximum running speeds, since athletes have to push their bodies forward as quickly as possible during all-out sprints, applying great amounts of force against the ground (45, 49). It is worth noting that these correlations were strong for both peak and MPP measures, reinforcing the notion that both variables are adequate to assess elite athletes, in both ballistic and traditional exercises (50).

Despite the amount of power production, this is the first study to show that the differences between JS and HS power outputs can be associated with sprint times. Although a previous study has shown that JS is more connected to speed and jump abilities than HS, to date, no research has assessed the mechanical differences between these two exercises. The fact that athletes with consistent differences in favor of JS are capable of sprinting faster has important implications in practical settings. Besides the capacity to generate higher levels of muscle power, this suggests that the capability to perform better in ballistic movements (19) may significantly influence maximum sprint performance. Possibly, the absence of deceleration during the concentric phase of JS (20, 54) makes this exercise more appropriate to optimize the actual performance of elite sprinters, who must execute their specific motor activities at very high velocities (20, 21, 38). On the other hand, the inherent braking phase of traditional exercises (i.e., HS) (48, 72) during their upward portions might reduce their selective influences on speed, at least in this group of very powerful athletes (18, 67). Therefore, coaches should be aware of the balance between the needs of their athletes before deciding the strategy that should be employed in each training period. Whilst traditional exercises may be used to build the foundation for subsequent power development (2, 32), ballistic movements (which allow for continued acceleration throughout the complete range of motion) (18, 67) should be preferred during the phases designed to maximize the speed-related adaptations (66). This is even more important in a group of top-level track and field athletes, who are at the extreme ends of speed and power performances.

In line with previous research (15, 49, 76), the vertical jump performance was shown to be highly associated with maximum running speed over different distances (i.e., from 10 to 60 m; r ~ 0.82). As such, Young et al. (83) demonstrated strong correlations between CMJ height and the fastest time to 10-m in a group of elite junior track and field athletes (r = 0.77). Similarly, in a study with young sprinters, Smirniotou et al. (76) revealed that SJ and CMJ are probably the best predictors of overall performance in 100 m, after comparing the predictive power of various strength and power parameters. These close relationships are possibly influenced by the intrinsic characteristics of jump tests. In effect, the height achieved during an SJ (or CMJ) is a measure able to express a mechanical value already corrected by the subjects' body mass (44). Essentially, if during a vertical jump an athlete jumps higher, he necessarily produces greater values of relative force and power ($N \cdot kg^{-1}$ and $W \cdot kg^{-1}$, respectively) than his weaker peer (17). As previously mentioned, these relative parameters (21) seem to have strict connections with top-level acceleration and sprint performance.

The same predictive ability for maximum running speed was also noted for the heights achieved during DJ assessments, without a clear trend between DJ 45-cm and DJ 75-cm (r ~ 0.82 for both tests, for all distances ranging from 10- to 60-m). Curiously, neither RSI nor EUR (variables generally used to quantify stretch-shortening function) (42, 58) were significantly correlated with sprint performance. These results are similar to those reported by other authors who have previously examined these interrelationships. For example, Barr and Nolte (5) suggested that the maximal height reached in a DJ is the most important DJ outcome, after analyzing a number of mechanical variables (including RSI) and observed that this measure presented the highest correlations with sprint times. Accordingly, it was verified that the CMJ-SJ ratio might influence solely the reaction times of elite sprinters, without significantly affecting their speed over a linear distance (76). Although it is recognized that stretch-shortening cycle actions are related to different sprint distances (49, 80), it is not clear if this assumption can be applied to elite sprinters. A possible explanation for this finding lies in the complexity of the sprint technique (43), which depends on the interaction between various neuromechanical and physiological factors (31, 44), thus reducing the impact of an "isolated component". Besides the amount of mechanical power - which can be favored by an optimized stretch-shortening cycle function (27, 37) - it has been supported that top-level sprinters rely substantially on the ability to orient the resultant force vector horizontally while accelerating (62, 63). Likewise, it is plausible to consider that the SSC assumes a more dominant role during top-speed phases (from 60- to 80-m), when the contact time is reduced and the necessity of generating force more rapidly increases (40, 81). That said, we should emphasize that our speed measurements were performed in short and mid distances (up to 60-m), perhaps compromising the level of correlations presented here. Probably, these relationships would have been significantly stronger if we had used longer distance sprint assessments (e.g., 100-m).

For the first time, functional performance tests and Vc were combined in the same predictive study involving track and field athletes. Although previous research has indicated that sprinters and jumpers present lower values of Td and Tc than long distance runners (46), the precise nature of the interaction between muscle mechanical measures, power capacity, and maximum running speed remains to be clarified. In this sense, the use of multiple regression models to examine the independent contributions of these potential sprint predictors may have an important role in the development of new and more effective training strategies. According to our findings, to maximize the actual performance of top-level sprinters, coaches should prioritize the use of workouts capable of simultaneously increasing relative power production and muscle contraction velocity. In this scenario, the implementation of mixed training programs seems to be very appropriate (66). Despite the lack of consensus about its optimal configuration (i.e., periodization model, frequency and loading conditions), the effectiveness of mixed approaches for improving many strength and power qualities in highly trained subjects is unquestionable (24, 66). Obviously, in top-level sports the selection of the ideal training strategies should be based on the personal responses of each athlete, which (in this specific case) can be controlled by consistent measurements of muscle mechanical parameters (74).

Indeed, the Vc has been shown to be useful for monitoring potential impairments in maximum speed of elite athletes throughout a competitive season (51). As explained before, this is a single index, able to integrate several of the reliable measures automatically provided by TMG (51, 70). It is well established that these standard TMG variables (i.e., Td, Tc, and Dm) should be collected at the maximum radial displacement of the muscle belly (68, 71). Nevertheless, to date, there is no evidence regarding the optimal way to assess Vc. For this reason, we used a fixed range of electrical stimulus (from 40 mA to 110 mA) for estimating Vc. With this approach, all athletes were assessed at all electrical intensities and, subsequently, the individual Vcs were calculated for each distinct condition for each athlete. Interestingly, different from the functional tests (where more powerful subjects can move higher loads at higher velocities, thus producing greater mechanical outputs), in these electrically induced muscle twitches (68), the lowest current amplitude (i.e., Vc 40 mA) was the most sensitive and appropriate stimulus to discriminate athletes with better speed and jump performances. Although the reasons for these discrepancies are unclear, we may speculate that the best sprinters and jumpers can effectively (and selectively) recruit more motor units even under lower electrical intensities. Hence, they probably produce higher amounts of force and power (8, 9) even at slower sprinting phases (i.e., acceleration phases), where the muscle activation is compromised due to the principle of size (i.e., in a given muscle contraction, smaller and slow motor units are recruited before the larger and fast ones) (28) and the necessity for rapid and synchronous initial firing rates from the motoneurons with a reduced interspike interval, to coordinate the contraction of many large muscles to break the inertia (7, 79). This fact could be associated to an optimized intrinsic muscle coordination pattern, which appears to be extremely dependent on the inherent characteristics of the subject (12, 29). Conversely, under higher electrical intensities, these highly trained athletes achieve similar levels of muscle activation (7, 12, 29), thus reducing the selective potential of these range of stimuli. Undoubtedly, this assumption is quite speculative and should be tested in more mechanistic studies.

An important point to note in our analyses is that the power production was directly assessed "on the barbell", without considering the subjects' body mass. Although we recognize that this has been a controversial issue leading to inconsistencies in reported power outputs in different populations (26), this approach was chosen based on our previous research and extensive experience with elite athletes (45, 47, 48, 50). In summary, instead of simply describing a mechanistic relation, we are focused on defining and selecting a more effective range of loads, which consider the force and velocity applied to the barbell at the same time (48, 55). This approach is proposed in opposition to the conventional loading method (i.e., percentages of 1RM), based solely on the scalar variable (i.e., mass) of the force equation (55). In fact, the "optimum power load" (assessed on the barbell) has been shown to be strongly related to specific sports performance, and capable of producing worthwhile increases in strength, speed and power qualities of top-level athletes from different disciplines (45, 47, 50, 52, 54).

This study was performed with top-level sprinters and jumpers during their competitive training season, which naturally restricts the complexity of our experimental design. While we recognize that our findings are limited by the cross-sectional nature of the dataset (which does not allow any conclusion about causality), we also believe that this work is an essential first step to guide further research in this field. The possibility of combining muscle mechanical measures provided by TMG and functional tests in the same predictive model opens new perspectives in comprehension of the multiple factors associated with sprint performance. Furthermore, since speed and acceleration are essential components in many sports (33) and considering that sprint events are usually decided by few hundredths of seconds (10), the identification of novel strategies to control and optimize sprinting ability may be extremely useful for coaches and strength and conditioning professionals. Together, these findings reinforce the notion that maximum running speed is a very complex physical capacity, which should be assessed and analyzed both in quantitative and qualitative terms.

PRACTICAL APPLICATIONS

This study may have important implications in the practical field, which must be viewed with caution considering the cross-sectional nature of the observations. Firstly, to maximize speed performance, elite athletes should primarily focus on increasing their relative muscle power production (i.e., W/kg). Probably, due to their mechanical characteristics, ballistic exercises (e.g., jump squats) are more indicated to optimize these neuromechanical capacities in sprinters and jumpers. To monitor the variations in sprint speed (and lower limb muscle power), practical vertical jump tests (i.e., SJ and CMJ) may be frequently applied throughout the training season, even in periods close to competitions. Similarly, the height achieved during DJ can also be used to reinforce the precision and accuracy of the “indirect speed measures”. Lastly, to examine the functional responses of skeletal muscles and discriminate athletes with different levels of speed and power performances, the Vc collected at 40 mA should be preferred over higher electrical stimulus intensities. Further investigations involving prospective designs and more comprehensive data collection (i.e., biomechanical analysis of sprint) are required to elucidate the exact causal nature of the associations presented herein.

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FIGURE CAPTION

Figure 1. Standardized differences in 40- and 60-m sprinting performance, squat and countermovement jump heights (SJ and CMJ, respectively), and mean propulsive and peak power outputs (MPP and PP, respectively) in the jump squat (JS) exercise between higher and lower Vc 40 mA groups. If the 90% confidence limits (error bars) did not cross smallest worthwhile change boundaries (effect size of ± 0.2; gray area), the effect was inferred as probably.

Table 1. Comparisons of sprinting and vertical jump performances, and mean propulsive and peak power (MPP and PP) outputs relative to athletes' body mass (REL) in the jump squat (JS) and half-squat (HS) exercises between male and female power track & field athletes.

	Male	Female	% of chances *rating*	ES (90% CL) *rating*
Time 10-m (s)	1.72 ± 0.07	1.84 ± 0.08	100/00/00 *Almost certain*	1.51 (0.65; 2.37) *Large*
Time 20-m (s)	2.86 ± 0.09	3.10 ± 0.08	100/00/00 *Almost certain*	2.88 (2.08; 3.69) *Very large*
Time 40-m (s)	4.89 ± 0.13	5.40 ± 0.08	100/00/00 *Almost certain*	4.46 (3.71; 5.22) *Nearly perfect*
Time 60-m (s)	6.84 ± 0.18	7.68 ± 0.13	100/00/00 *Almost certain*	5.21 (4.45; 5.98) *Nearly perfect*
SJ (cm)	44.3 ± 6.0	34.6 ± 4.0	100/00/00 *Almost certain*	1.86 (1.10; 2.62) *Large*
CMJ (cm)	46.7 ± 6.7	36.9 ± 4.3	100/00/00 *Almost certain*	1.68 (0.93; 2.44) *Large*
DJ 45 CT (ms)	411.4 ± 82.3	294.4 ± 54.0	100/00/00 *Almost certain*	1.62 (0.84; 2.40) *Large*
DJ 45 Height (cm)	42.5 ± 5.6	33.1 ± 4.4	100/00/00 *Almost certain*	1.81 (1.01; 2.61) *Large*
DJ 45 RSI	1.08 ± 0.33	1.17 ± 0.31	17/28/55 *Unclear*	0.27 (-0.56; 1.10) *Small*
DJ 75 CT (ms)	414.4 ± 67.0	304.1 ± 64.8	100/00/00 *Almost certain*	1.64 (0.80; 2.47) *Large*
DJ 75 Height (cm)	42.1 ± 6.8	30.0 ± 4.7	100/00/00 *Almost certain*	2.00 (1.21; 2.78) *Large*
DJ 75 RSI	1.04 ± 0.27	1.03 ± 0.26	30/32/30 *Unclear*	0.06 (-0.78; 0.89) *Trivial*
MPP REL JS ($W.kg^{-1}$)	15.9 ± 1.9	11.7 ± 1.3	100/00/00 *Almost certain*	2.50 (1.71; 3.28) *Very large*
PP REL JS ($W.kg^{-1}$)	36.0 ± 4.9	29.5 ± 2.9	100/00/00 *Almost certain*	1.55 (0.79; 2.32) *Large*
MPP REL HS ($W.kg^{-1}$)	11.6 ± 1.5	9.31 ± 1.16	99/01/00 *Very Likely*	1.68 (0.76; 2.61) *Large*
PP REL HS ($W.kg^{-1}$)	27.6 ± 3.9	22.2 ± 3.3	98/01/01 *Very Likely*	1.46 (0.51; 2.40) *Large*

Note: ES: effect sizes; CL: confidence limits; SJ: squat jump; CMJ: countermovement jump; DJ 45: drop jump in 45 cm; DJ 75: drop jump in 75 cm; CT: contact time; RSI: reactive strength index.

Table 2. Comparisons of the contraction velocity (Vc) in different intensities for the rectus femoris (RF) and biceps femoris (BF) between male and femalepower track & field athletes.

	Male	Female	% of chances	ES (90% CL)
Vc RF 40 mA (mm.ms^{-1})	0.83 ± 0.22	0.56 ± 0.36	89/07/03 *Likely*	0.89 (0.05; 1.82) *Moderate*
Vc RF 60 mA (mm.ms^{-1})	1.01 ± 0.30	0.95 ± 0.57	44/29/27 *Unclear*	0.12 (-0.83; 1.06)*Trivial*
Vc RF 80 mA (mm.ms^{-1})	1.18 ± 0.33	1.22 ± 0.52	29/30/41 *Unclear*	0.09 (-0.84; 1.02)*Trivial*
Vc RF 100 mA (mm.ms^{-1})	1.25 ± 0.41	1.35 ± 0.57	22/28/50 *Unclear*	0.21 (-0.70; 1.11) *Small*
Vc RF 110 mA (mm.ms^{-1})	1.31 ± 0.47	1.43 ± 0.58	24/30/46 *Unclear*	0.15 (-0.73; 1.02)*Trivial*
Vc RF Max (mm.ms^{-1})	1.35 ± 0.46	1.43 ± 0.58	24/29/47 *Unclear*	0.16 (-0.72; 1.04)*Trivial*
Vc BF 40 mA (mm.ms^{-1})	0.43 ± 0.47	0.42 ± 0.41	36/31/33 *Unclear*	0.02 (-0.85; 0.90)*Trivial*
Vc BF 60 mA (mm.ms^{-1})	0.52 ± 0.43	0.52 ± 0.42	34/31/35 *Unclear*	0.00 (-0.88; 0.89) *Trivial*
Vc BF 80 mA (mm.ms^{-1})	0.54 ± 0.43	0.64 ± 0.43	19/27/54 *Unclear*	0.25 (-0.65; 1.14)*Small*
Vc BF 100 mA (mm.ms^{-1})	0.59 ± 0.44	0.64 ± 0.42	26/30/44 *Unclear*	0.13 (-0.75; 1.01)*Trivial*
Vc BF 110 mA (mm.ms^{-1})	0.59 ± 0.44	0.66 ± 0.50	25/28/46 *Unclear*	0.15 (-0.79; 1.09)*Trivial*
Vc BF Max (mm.ms^{-1})	0.63 ± 0.44	0.69 ± 0.46	27/29/44 *Unclear*	0.12 (-0.79; 1.03)*Trivial*

Note: Vc values were multiplied by 10 to facilitate visualization and interpretation; ES: effect sizes; CL: confidence limits.

Table 3. Correlation between sprinting time and vertical jumps in power track & field athletes.

	SJ	CMJ	EUR	DJ 45 CT	DJ 45 Height	DJ 45 RSI	DJ 75 CT	DJ 75 Height	D75 RSI
Time 10-m	-0.79*	-0.76*	0.19	-0.14	-0.75*	-0.31	-0.31	-0.81*	-0.43
Time 20-m	-0.87*	-0.83*	0.22	-0.33	-0.82*	-0.18	-0.46	-0.85*	-0.34
Time 40-m	-0.88*	-0.84*	0.19	-0.42	-0.85*	-0.14	-0.51*	-0.85*	-0.33
Time 60-m	-0.83*	-0.80*	0.20	-0.48	-0.79*	-0.06	-0.55*	-0.81*	-0.24
SJ		0.98*	-0.07	0.31	0.95*	0.32	0.38	0.91*	0.49
CMJ			0.13	0.31	0.95*	0.33	0.36	0.89*	0.50*
EUR				0.07	0.09	0.03	-0.06	-0.01	0.06
DJ 45 CT					0.23	-0.71*	0.92*	0.34	-0.53*
DJ 45 Height						0.48	0.29	0.93*	0.64*
DJ 45 RSI							-0.63*	0.34	0.95*
DJ 75 CT								0.46	-0.49*
DJ 75 Height									0.54*

Note: SJ: squat jump; CMJ: countermovement jump; EUR: eccentric utilization ratio (calculated from the differences between SJ and CMJ performances); DJ 45: drop jump in 45 cm; DJ 75: drop jump in 75 cm; CT: contact time; RSI: reactive strength index; *$P < 0.05$.

Table 4. Correlation between sprinting time, vertical jumps, and mean propulsive power (MPP) and peak power (PP) in the jump squat (JS) and half-squat (HS) exercises inpower track & field athletes.

	MPP RELJS	PP RELJS	MPP RELHS	PP REL HS
Time 10-m	-0.73*	-0.66*	-0.59*	-0.53*
Time 20-m	-0.84*	-0.75*	-0.66*	-0.65*
Time 40-m	-0.86*	-0.74*	-0.67*	-0.70*
Time 60-m	-0.83*	-0.72*	-0.64*	-0.68*
SJ	0.91*	0.78*	0.66*	0.69*
CMJ	0.92*	0.81*	0.67*	0.69*
DJ 45 CT	0.32	0.13	0.32	0.12
DJ 45 Height	0.91*	0.81*	0.82*	0.86*
DJ 45 RSI	0.28	0.37	0.23	0.42
DJ 75 CT	0.36	0.18	0.35	0.19
DJ 75 Height	0.87*	0.73*	0.69*	0.68*
DJ75RSI	0.45	0.48	0.32	0.47

Note: SJ: squat jump; CMJ: countermovement jump; DJ 45: drop jump in 45 cm; DJ 75: drop jump in 75 cm; CT: contact time; RSI: reactive strength index; MPP and PP in both exercises are presented relative to athlete's body mass (REL); **P*< 0.05.

Table 5. Correlation between sprinting time and the differences between countermovement and squat jumps, and the differences in the power outputs between jump squat and half-squat exercises.

	Jump differences	MPP differences	PP differences
Time 10-m	-0.06	-0.69*	-0.38
Time 20-m	-0.05	-0.72*	-0.29
Time 40-m	-0.07	-0.71*	-0.26
Time 60-m	-0.04	-0.81*	-0.25

Note: MPP: mean propulsive power; PP: peak power; both power measures were relative to the athletes' body mass; *$P < 0.05$.

Table 6. Correlation between contraction velocity (Vc) in the rectus femoris (RF) and biceps femoris (BF) and sprinting time, vertical jumps, and mean propulsive power (MPP) and peak power (PP) in the jump squat (JS) and half-squat (HS) exercises.

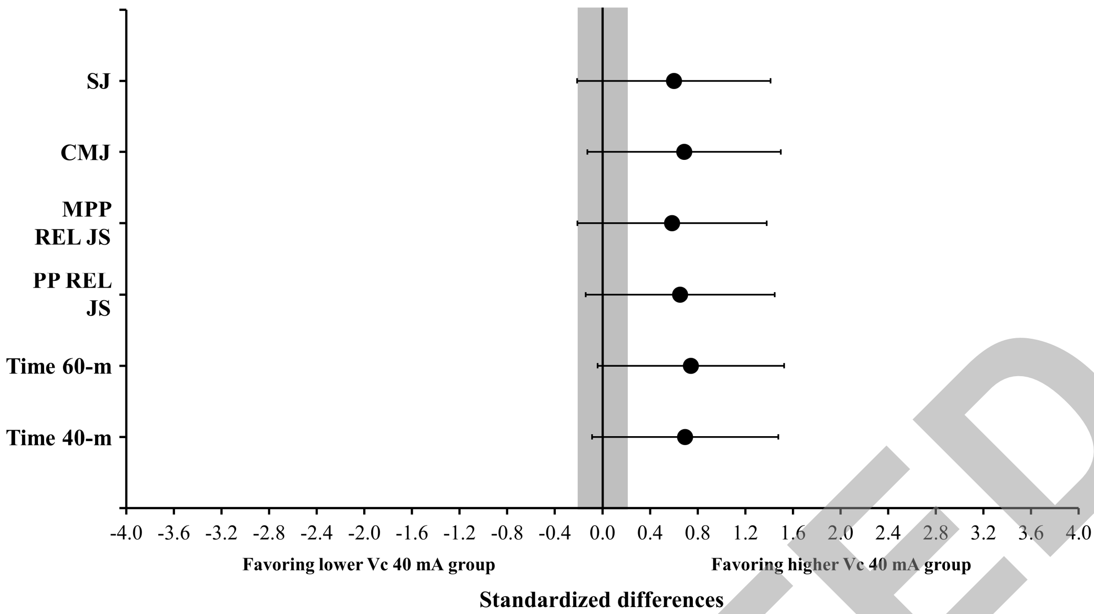
	Vc RF 40 mA	Vc RF 60 mA	Vc RF 80 mA	Vc RF 100 mA	Vc RF 110 mA	Vc RF Max	Vc BF 40 mA	Vc BF 60 mA	Vc BF 80 mA	Vc BF 100 mA	Vc BF 110 mA	Vc BF Max
T10	-0.30	-0.23	-0.14	-0.11	-0.14	-0.37	-0.06	0.02	0.04	-0.01	0.00	-0.30
T20	-0.41	-0.24	-0.11	-0.08	-0.11	-0.18	-0.08	0.00	0.05	0.00	0.00	-0.17
T40	-0.46	-0.19	-0.06	-0.04	-0.08	0.01	-0.09	-0.02	0.06	0.02	0.02	-0.07
T60	-0.46	-0.15	0.00	0.01	-0.03	0.10	-0.08	-0.01	0.07	0.03	0.03	-0.01
SJ	0.48	0.33	0.30	0.26	0.29	0.14	0.13	0.02	-0.04	-0.03	-0.05	0.24
CMJ	0.47	0.39	0.37	0.33	0.35	0.16	0.20	0.10	0.04	0.04	0.01	0.30
DJ 45 CT	0.44	0.05	-0.02	-0.16	-0.21	-0.12	-0.18	-0.12	-0.25	-0.24	-0.21	-0.32
DJ 45 Height	0.44	0.29	0.33	0.31	0.34	0.35	0.07	0.07	0.00	0.02	0.04	0.53*
DJ 45 RSI	-0.10	0.07	0.21	0.30	0.37	0.35	0.15	0.12	0.20	0.20	0.20	0.68*
DJ 75 CT	0.46	-0.06	-0.15	-0.25	-0.31	0.02	-0.31	-0.31	-0.40	-0.38	-0.33	-0.19
DJ 75 Height	0.43	0.14	0.16	0.14	0.17	0.31	-0.05	-0.05	-0.12	-0.08	-0.07	0.44
DJ 75 RSI	-0.01	0.12	0.25	0.33	0.41	0.27	0.22	0.23	0.26	0.28	0.25	0.64*
MPP REL JS	0.58*	0.44	0.34	0.29	0.32	0.20	0.14	0.11	0.03	0.05	0.01	0.37
PP REL JS	0.51*	0.54*	0.42	0.38	0.41	0.18	0.33	0.26	0.22	0.24	0.21	0.46
MPP REL HS	0.44	0.28	0.22	0.18	0.20	0.61*	0.02	0.05	-0.02	0.02	0.06	0.49
PP REL HS	0.35	0.19	0.13	0.13	0.17	0.50	0.04	0.04	-0.02	0.02	0.06	0.54*

Note: SJ: squat jump; CMJ: countermovement jump; DJ 45: drop jump in 45 cm; DJ 75: drop jump in 75 cm; CT: contact time; RSI: reactive strength index; MPP and PP in both exercises were relative to athlete's body mass (REL); *$P < 0.05$.

Table 7. Prediction (R^2) of the sprinting performance in the different distances using amultiple regression analysis combining the contraction velocity (Vc) at 40 mA, the vertical jump heights and the power outputs in the jump squat (JS) and half-squat (HS) exercises as independent variables.

Independent variables		**R^{2*}**			
		Time 10-m	**Time 20-m**	**Time 40-m**	**Time 60-m**
	SJ	0.69	0.84	0.87	0.79
	CMJ	0.62	0.77	0.81	0.73
	DJ 45 Height	0.59	0.73	0.80	0.72
Vc 40 mA	**DJ 75 Height**	0.68	0.79	0.82	0.76
	MPP REL JS	0.56	0.75	0.78	0.73
	PP REL JS	0.45	0.60	0.61	0.59
	MPP REL HS	0.36	0.44	0.44	0.41
	PP REL HS	0.31	0.44	0.50	0.47

Note: SJ: squat jump; CMJ: countermovement jump; DJ 45: drop jump in 45 cm; DJ 75: drop jump in 75 cm; MPP: mean propulsive power; PP: peak power; MPP and PP in both exercises are presented relative to athlete's body mass (REL); *P< 0.05 for all R^2 values.


SJ
CMJ
MPP
REL JS
PP REL
JS
Time 60-m
Time 40-m
-4.0 -3.6 -3.2 -2.8 -2.4 -2.0 -1.6 -1.2 -0.8 -0.4 0.0 0.4 0.8 1.2 1.6 2.0 2.4 2.8 3.2 3.6 4.0
Favoring lower Vc 40 mA group
Favoring higher Vc 40 mA group
Standardized differences