Jump phase characteristics in high level 400 m sprinters – using different jump types to assess lower-body strength/power characteristics

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Headline

There are multiple factors influencing sprinters running velocity and the ability to increase running velocity. The 400 m sprint is usually known as a speed endurance event that demands a high level of anaerobic glycolysis, buffering capacity and aerobic processes to maintain maximum velocity (1,2,3,4). Although stride frequency and stride length have been shown to also influence sprinting speed, stride length seems to be the more important biomechanical parameter when distinguishing between levels of performance in 400 m races (5). Elite sprinters are able to apply more force into the ground, resulting in longer stride lengths, faster stride frequencies, and subsequently, faster sprint times compared to less experienced sprinters (7,8). Although 400 m race is classified as "sprint distance" it is characterized by unique metabolic, neuromuscular, and technical requirements in comparison to 100 and 200 m races (5,9). The countermovement jump (CMJ) is primarily used to measure an athlete's explosive lower-body power and neuromuscular fatigue (10). A relationship between 400 m performance and average height of 30 s repeated CMJs (Bosco test) was found but not with single CMJ height performance (11, 12). The lack of association between jump height (JH) and 400 m performance may be due to the fact that athletes' may employ varying movement strategies (such as increasing the time of force application) to achieve a desired outcome (e.g. jump height) and therefore jump performance may be influenced by a variety of factors. However, comprehensive insight into athletes' neuromuscular function can be gained through detailed analyses using force plates. Different jump types (e.g. squat jumps, weighted jumps) are used in vertical jump testing and its essential to provide information how to incorporate these tests into training program. Despite growing popularity of force plates in S&C we are not aware of any research focusing on jump phase characteristics in high – level 400 m sprinters. Hence, to increase our knowledge of high level performance and to collect up-to date data related to high-level sprinters, more investigations need to be undertaken (13). This knowledge could be used by coaches in order design better training programs and select most important variables. Therefore, the primary purpose of the study was to delineate physical characteristics of two high - level 400 m sprinters using different types of jumps.

Aim

The aim of this study was to describe the CMJ phase characteristics of two high –level 400 m sprinters and gain better understanding of lower-limb neuromuscular profile.

Methods

Athletes

Two international level 400 m sprinters (Athlete 1: age 31y, body mass: 74kg, years of training: 15 and Personal Best (PB) : 45.65s Athlete 2: age: 25y, body mass: 65 kg, years of training: 9y and PB: 46.19 s were tested. These data arose from the monthly monitoring program in which each athlete's motor abilities are routinely measured over the course of the season. Therefore, clearance from the ethics committee board was not required (14). Nevertheless, the study conformed to the recommendations of the Declaration of Helsinki. Both international level sprinters competed at IAAF World and European Championships while Athlete 1 is a 400 m Relay Indoor World Record holder from 2018 (3:01:77).

Design

The testing day took place at the beginning of the recovery week (4th week) of the strength – speed block and 3 days before the Regional Track and Field meet (July 2020). Athletes had regularly performed jump testing throughout the year and were familiar with the testing protocol. Body weight squat jumps (SJ), countermovement jumps (CMJ), CMJ with arm swing (CMJas) and weighted countermovement jumps (CMJ 20 kg) were assessed. SJs were performed from an internal knee angle of 90°, which was measured using a goniometer. Body weight and weighted CMJs were performed from a standing position with hands on the hips (body weight) or with the barbell on their upper back (weighted). CMJas test followed the same procedure as CMJ, however, participants were permitted to use an arm swing. During each CMJ type test, athletes performed a rapid countermovement to a self-selected depth and were instructed to jumps as quick and high as possible. The start of the jump began with a verbal "three, two, one, jump!" countdown. Athletes commenced each jump test with a 50% and 75% effort warmup-up jump, followed by 3 maximal effort jumps.

Methodology

Each jump was performed with each foot on a portable force plate (35 cm by 35 cm each, PASPORT force plate, PS-2141 PASCO Scientific, California, USA) where vertical force at 1000 Hz, using Pasco Capstone software (PASCO Scientific, California, USA) was recorded. All raw vertical force – time data was analysed with an open source vertical jump analysis application (15). Sprinters were instructed to stand still (i.e., quiet standing) for at least one second at the beginning of the data collection period for determination of body weight (BW) and the jump initiation threshold.

The jump initiation threshold is defined in the jump analysis application as 5 standard deviations (SD) below the BW determined during quiet standing. The first point falling be-

Table 1. Jump phase variables for SJ, CMJ, CMJas and weighted CMJ (Mean ± SD).

	Athlete 1				Athlete 2			
Performance 400 m								
Personal Best (s)	45.65				46.19			
Regional T&F Meet (s)	46.94				47.50			
CMJ Variable	**SJ**	**CMJ**	**CMJas**	**CMJ 20 kg**	**SJ**	**CMJ**	**CMJas**	**CMJ 20 kg**
Jump height (cm)	48 ± 2.8	52.3 ± 0.6	62.7 ± 0.6	39 ± 0.0	49.3 ± 1.4	50.5 ± 1.1	57.2 ± 1.8	32.6 ± 0.1
Time to take off (s)	0.33 ± 0.03	0.843 ± 0.09	0.967 ± 0.04	0.77 ± 0.01	0.451 ± 0.12	0.911 ± 0.012	1.091 ± 0.01	1.139 ± 0.05
RSImod		0.62 ± 0.09	0.65 ± 0.02	0.51 ± 0.01		0.56 ± 0.08	0.52 ± 0.01	0.28 ± 0.01
CMJ depth (cm)		36.9 ± 1.5	41.9 ± 0.09	38.5 ± 2.3		39.8 ± 1.9	46 ± 1.1	43.1 ± 0.02
Unweghting phase time (s)		0.46 ± 0.1	0.539 ± 0.042	0.306 ± 0.014		0.458 ± 0.117	0.541 ± 0.04	0.552 ± 0.055
Braking phase time (s)		0.14 ± 0.006	0.163 ± 0.006	0.182 ± 0.005		0.175 ± 0.01	0.217 ± 0.02	0.226 ± 0.00
Propulsion phase time (s)		0.241 ± 0.004	0.266 ± 0.01	0.278 ± 0.005		0.279 ± 0.008	0.333 ± 0.007	0.361 ± 0.005
Peak Eccentric Force (N/kg)		27.12 ± 0.28	25.37 ± 0.24	28.29 ± 0.73		25.32 ± 0.4	21.11 ± 0.87	26.33 ± 0.55
Peak Concentric Force (N/kg)	26.49 ± 0.8	27.45 ± 0.2	27.01 ± 0.46	28.47 ± 0.71	26.68 ± 0.02	25.29 ± 0.37	25.83 ± 0.51	26.3 ± 0.5
Peak Eccentric Velocity (m/s)		1.7 ± 0.05	1.85 ± 0.03	1.63 ± 0.13		1.52 ± 0.05	1.31 ± 0.03	1.46 ± 0.01
Peak Concentric Velocity (m/s)	3.13 ± 0.07	3.3 ± 0.01	3.59 ± 0.02	2.84 ± 0.02	3.19 ± 0.03	3.23 ± 0.01	3.42 ± 0.04	2.67 ± 0.02
Peak Eccentric Power (W/kg)		31.24 ± 2.14	31.02 ± 2.98	31.82 ± 6.05		21.73 ± 0.63	16.56 ± 1.03	24.58 ± 0.21
Peak Concentric Power (W/kg)	69.38 ± 0.68	70.34 ± 1.0	80.76 ± 1.82	66.44 ± 0.03	70.14 ± 0.28	64.03 ± 0.7	73.88 ± 2.71	59.2 ± 0.14
Net Impulse (N*s/kg)	3.09 ± 0.04	3.2 ± 0.02	3.5 ± 0.01	3.51 ± 0.01	3.11 ± 0.04	3.14 ± 0.03	3.35 ± 0.05	3.3 ± 0.0
AvgRFD (N/kg/s)	65.72 ± 15.93	29.26 ± 5.26	19.9 ± 1.26	31.9 ± 2.74	49.77 ± 17.45	25.5 ± 5.86	15.93 ± 0.44	17.53 ± 0.14
Force@Peak Power (N/kg)	25.19 ± 0.55	23.75 ± 0.41	25.42 ± 0.69	25.78 ± 0.3	25.04 ± 0.15	22.01 ± 0.27	24.48 ± 0.75	24.16 ± 0.09
Velocity@Peak Power (m/s)	2.75 ± 0.09	2.96 ± 0.02	3.17 ± 0.02	2.58 ± 0.02	2.8 ± 0.02	2.9 ± 0.02	3.01 ± 0.04	2.45 ± 0.01

RSImod- Reactive strength index - modified; avgRFD - average Rate of force development.

low this threshold is flagged, and the data preceding this point are screened for pre-jump movements. Following the screening process, the app searches backward through the data for the first point approximately matching the BW found during quiet standing. Approximate takeoff and touchdown locations are determined by searching forward from peak vertical ground reaction force (vGRF) and backward from peak landing vGRF, respectively. In each case, the first point falling below a threshold of 10 N is flagged, and the middle 50% of data between these points is used to determine the true threshold for takeoff and touchdown (similar to jump initiation, mean vGRF plus 5SD). Following threshold identification, the jump analysis application re-performs the forward and backward searches for takeoff and touchdown using the new threshold. The jump analysis application calculates net impulse via trapezoidal integration of the force-time data, while centre of mass (COM) velocity is calculated by normalizing the impulse to body mass. Jump height is then determined from the impulse-momentum theorem using takeoff velocity via TOV jump height = $\mathrm{TOV}^2/2g$, where TOV = takeoff velocity and $g = 9.81$ m·s^{-2} (16). Aside from the flight phase, three additional phases are determined prior to takeoff: unweighting, braking, and propulsion. The unweighting phase represents the area of the forc e-time curve that is below BW. The braking phase continues from the end of the unweighting phase until the instant COM velocity increases to zero. Finally, the propulsion phase spans the end of the braking phase to the instant of takeoff. Readers are referred to McMahon et al. (17) for further discussion on phase determination. Time to takeoff (TTT) represents the entirety of the jump from initiation to takeoff, while RSI-modified (RSImod) is calculated as the jump height divided by TTT. For SJ, quiet standing mean vGRF + 5SD of quiet standing is used as the jump initiation threshold. Average rate of force development (avgRFD) represents the difference in peak force prior to takeoff and the force at jump initiation divided by the time required to reach peak force.Readers who would like more in-depth information concerning phase and variable calculations are referred to Sams (15), where they may read the documentation and commented source code for the application. All kinetic data were divided by body mass to allow for a normalised comparison between sprinters.

Results

For each gross measure, the mean output of the three CMJ trials was taken forward for descriptive analysis. Comparisons of body weight SJs and CMJs phase variables between athletes are presented in table 1. Results are expressed as mean ± SD.

Discussion

This is the first study presenting CMJ output variables and movement strategy in high level 400 m sprinters. Because only data of two athletes were collected, the discussion will be presented as a narrative which serves as a useful communication channel for coaches (18).

It has usually been agreed that anaerobic capacity is the main factor discriminating 400 m performance (2). Nevertheless, the need to generate high forces in a small amount of time indicates that the force-velocity relationship is an important contractile property of muscle in terms of limiting maximum sprinting speed (19). The variability of 400 m finalists performance during IAAF World Athletics Championships (Doha 2019) was 1.04% which was lower than the difference between subject 1 and 2 in the current study (1.17%). In a real-world scenario, the gap in performance between athlete 1 and 2 is comparable to being in the final or not. Therefore, there is a significant difference in performance level between subjects which was also mirrored in neuromuscular indices. The main finding of this study was, that athlete 1 produced a significantly greater peak power, force, and velocity in both eccentric and concentric phases of each CMJ type. Considering that these variables are calculated from single data points, they only represent 1 ms of the movement's kinetic and kinematic history. Thus, it is essential to focus on mechanistic changes in the CMJ which reflect movement (CMJ) strategy and output identifying training-induced fatigue and/or adaptation.

Weighted and Unweighted CMJ Comparison: Force-velocity implications and strength levels. Greater jump height and shorter time to take off (TTT) resulted in higher RSImod in athlete 1. In line with previous research (20), athlete 1 can perform the CMJ with a shorter TTT because he reduced COM displacement during the combined unweighting and braking phases (shallower squat), which thus reducing the braking and propulsion times that comprise the majority of the total TTT calculation. The main mechanism behind shorter TTT may have been due to superior strength level. It was reported in literature that stronger athletes exhibit shorter unweighted phase durations as compared to less-strong athletes (21) and generally faster countermovements (22,23). Greater unweighting is theorized to have led to an optimization of stretch-shorten cycle (SSC) function, which contributed to the enhanced jump performance (23). Confirmation of superior strength levels in athlete 1 could be done by comparing weighted and unweighted jumps. Kraska et al. (24), found moderate to strong correlations between percent loss in CMJ height (unweighted vs weighted JH) and isometric peak force. In other words, stronger athletes jump higher and show smaller decrements in JH with 20kg load in comparison to unweighted (body weight) CMJ. This fact strongly supports our hypothesis as in relationship was also observed in the current study, where JH decrements of 25% and 35% were observed for athletes 1 and 2, respectively. Since athlete 1 developed greater force across smaller range of motion during eccentric phase, the stiffness of the system is greater than in athlete 2. Analysis of the velocity and stride parameters revealed that during last 50 m of the 400 m race, the decrease in stride frequency was more important than the decrease in length. This decrease in stride frequency observed under fatigue has been shown to be related to the decrease in vertical leg stiffness (5). Thus, it can be suggested that athlete 1 is better prepared to translate the momentum developed into force and therefore, possesses a higher vGRF which translates to superior sprinting performance (7,8,23).

Squat Jump Comparison: Concentric force production, propulsive impulse. It has been well established that enhancement of power in the propulsion (concentric) phase is largely dependent on the alterations in number of eccentric phase variables (22,23). Greater force developed during eccentric phase may have led to the higher force level at the beginning of the concentric phase and thus, positively affect maximal power in athlete 1. Interestingly, in contrast to CMJs, a divergent pattern of results in SJ test was observed. Athlete 2 produced marginally higher force, velocity, power and jump performance because of a greater propulsive impulse in comparison to athlete 1. Impulse is a product of force and time in the simplest of terms. However, it was evident that athlete 2 had a longer contraction time, which provided an opportunity for the athlete to apply force for a longer period of time. The discrepancy in TTT between the two athletes, despite the same start position (90° knee angle) can be explained by difference in lower limb segment lengths and, in turn, different push – off distances. It has been demonstrated that different push-off distances and times, result in varying levels of power output (25). Therefore, it is suggested that propulsion peak power should be controlled by push – off distance when inter-individual interpretations of jumps are made.

CMJ vs CMJas Comparison: Energy transfer, coordination, jump height augmentation. Greater jump heights (Athlete 1 - 16.6%, Athlete 2 – 11.7%) were observed in CMJas when compared to CMJ, which is in agreement with previous observations (26). The inclusion of CMJas in the current test battery is justified by the fact that the arm swing performed in both sprinting and jumping could fulfill a similar mechanical role by increasing ground reaction forces and, thus, including CMJas yields a higher degree of sport specificity (27). Greater jumping performance in CMJas than in CMJ is believed to be an indicator of a better energy transmission and coordination (26, 28). Nevertheless, higher JH for CMJas test were obtained by the athletes due to a greater countermovement depth and longer force application which resulted in a larger impulse than in CMJ. Interestingly, when CMJas was compared to CMJ, athlete 1 increased while athlete 2 decreased in eccentric peak velocity. The mechanism behind this is unknown and examination of more subjects is required. However, it can be concluded that athlete 1 utilized a greater arm-swing for jump height augmentation.

While it appears that portable force plate systems recently became more affordable for coaches and scientists, it is essential to gain better understanding of direction and magnitude of an athlete's adaptation process in various sport disciplines. Furthermore, using different modes of jumping assessments can provide greater insight into possible mechanisms that comprise one's explosive performance state. Because data were collected on only two athletes in the present investigation, future studies with larger sample sizes are needed to elucidate which jump mode and jump-performance variable is related to 400 m performance.

Practical Applications

- Results of this study suggest that JH in SJ is not sensitive discriminator of performance, but this statement refers only to sprinters presented in the current study.
- With regards to CMJ and CMJas test, Athlete 2 relies on a larger countermovement displacement and, thus, a longer propulsion time to attain JH. Relying on propulsion net impulse that is comprised of a longer time rather than a larger force to attain a given JH is, however, an impractical solution given that there is a limited amount of time available to produce high levels of force during many sporting tasks.
- Comparisons of different jump types may provide more insight into athletes' lower body strength/power characteristics.

Limitations

- Main limitation of this study was the very small sample size. Therefore, it remains unclear if the results are generalisable for 400 m sprinters.
- Sprinters were tested during training mesocycle therefore fatigue levels could mask fitness level.

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