Sprint mechanical and kinematic characteristics of national female track and field champions and lower-level competitors

THEODOSIA ECONOMOU¹, IOANNIS STAVRIDIS², MARIA ZISI³, EFSTRATIOS FRAGKOULIS⁴,
GEORGIA OLANEMI-AGILARA⁵, GIORGOS PARADISIS⁶

^{1,2,3,4,5,6,...} Sports Performance Laboratory, School of Physical Education & Sport Science, National & Kapodistrian University of Athens, Athens, GREECE;

Published online: November 30, 2021

(Accepted for publication November 15, 2021)

DOI:10.7752/jpes.2021.s6441

Abstract

The current study examines the sprint mechanical and kinematic characteristics between national female track and field champions (NC) and lower-level female competitors (LL). Sixteen female athletes (8 National Champions, 8 Lower-level competitors) participated in this investigation. The testing procedures consisted of two maximal 30-m sprints. The velocity-time data, captured by three high-speed cameras, was used to calculate the variables of the horizontal F-v profile (theoretical maximal values of force [F_0], velocity [V_0], power [P_{max}], the proportion of the theoretical maximal effectiveness of force application in the antero-posterior direction [RF_{max}], the rate of decrease in the ratio of horizontal force [DRF]) and essential kinematics characteristics. The NC female athletes showed higher values for P_{max} ($t = 3.26$, $p = 0.006$), V_0 ($t = 6.27$, $p = 0.000$) and RF_{max} ($t = 2.58$, $p = 0.022$) compared to LL female competitors. No statistical differences were observed for F_0 ($t = 1.027$, $p = 0.32$) and DRF ($t = 0.917$, $p = 0.375$). Mean running velocity, step frequency and contact time were higher in all but one (0-5 m) 5-m distance intervals of the 30-m sprint. No differences were found in the mean step length, relative step length and flight time in the intervals (0-5, 5-10, 10-15, 15-20, 20-25, and 25-30 m). The faster female athletes in our study demonstrated the capacity to reach superior running velocities, develop larger horizontal forces at higher velocities, apply more effectively the force on the ground in the acceleration phase, show higher values of step frequencies and spent less time in contact with the ground than slower athletes.

Key Words: sprinting mechanics, acceleration, females, power capacity

Introduction

Sprinting is an essential component of performance in many sports and is crucial parameter in specific track-and-field events. In sprint running, lower limbs must produce high forces in order to accelerate, and sustain high horizontal speeds. The maximal amount of force produced by the neuromuscular system during sprinting depends on the running velocity (Morin & Samozino, 2016). The mutual dependency among force, velocity, and power producing capacities of leg muscles could be well described using the inverse linear force-velocity (F-v) and the parabolic power-velocity (P-v) relationships (Morin et al., 2011, 2019; Samozino et al., 2016). During the sprint acceleration phase, the F-v and P-v relationships characterize the change in the athlete's maximal horizontal force and power production capabilities when the running velocity increases. Sprinter's theoretical maximum power output (P_{max}), theoretical maximum horizontal force (F_0), theoretical maximum horizontal velocity (V_0), the ratio of the total force production which directed in the horizontal direction (RF_{max}) and the decrease in the ratio of horizontal force as the running velocity increased (DRF), can be easily estimated using established field methods (Morin et al., 2011, 2019; Samozino et al., 2016). These variables are key determinant factors for sprint-acceleration performance (Morin & Samozino, 2016). Furthermore, the sprint mechanical profile has been used to distinguish the differences in the mechanical properties of athletes from different sports, exercise levels, age and sex (Alcazar et al., 2018; Jiménez-Reyes et al., 2018; Slawinski & Morin, 2017; Stavridis et al., 2019).

Speed is a product of step length and step frequency and an increase in one of these two variables, or both, will consequently result in the achievement of higher running speed as long as the other one does not undergo a proportionately similar or larger decrease (Hunter et al., 2004; Paradisis et al., 2019). According to previous researches both stride frequency and length rise with increasing running velocity (Brughelli et al., 2011; Weyand et al., 2000) whereas flight and contact time decrease with increasing speed up to maximum velocity phase (Brughelli et al., 2011).

It is known that high-level athletes can apply higher forward-oriented ground reaction forces during the acceleration phase and optimizing the levels of vertical impulses during the maximal velocity phase compared to lower-level competitors (Morin et al., 2011.; Nagahara et al., 2018; Slawinski et al., 2017). Previous studies have investigated the gender-related differences in the sprint start's kinetic and kinematic performance indices (Debaere et al., 2013; Mirkov et al., 2020). The most prominent differences were detected for the kinetic

variables with males exhibiting higher maximal and average force production and higher force impulse values (Debaere et al., 2013). Moreover, Slawinski et al. (2017) showed that world-class female sprinters achieve peak velocity during a sprint earlier than world-class men sprinters and that the peak velocity was lower than in men sprinters. Furthermore, the comparison of the sprint mechanical F-v profile between soccer and futsal men and women players reveal that men soccer players presented an overall enhanced F-v profile compared to women and also, high-level men and women athletes presented higher values of F_0 , V_0 , P_{max} and RF_{max} compared to their low level counterparts (Jiménez-Reyes et al., 2019).

As with most research in sports performance settings the majority of evidence in sprint running research is derived from studies with male athletes (Cross et al., 2015; Nagahara & Girard, 2021; Paradis et al., 2019; Haugen et al., 2019). Whilst very recent research has offered an informative and comprehensive account on this topic by also including analysis of the maximum velocity phase (Gleadhill & Nagahara, 2021) the need to understand the interaction between performance level and mechanical qualities is key to our understanding of the individuality nature of mechanical profiles. To this end, we adopted the power-force-velocity profiling method (Morin et al., 2019; Samozino et al., 2016) alongside kinematic analysis to compare the physical, functional and performance differences between national female track and field champions and low-level female competitors. This information enriches the existing sprinting literature on female sprinting and provides a better insight into performance determinants affecting acceleration rates in female athletes. Also, the results of the current study assist coaches to diversify training programs to meet individual and level-specific needs. Firstly, it was hypothesized that high level female athletes would display more favorable mechanical characteristics compared to lower-level females during sprinting performance. Secondly, we hypothesized that high level female athletes present higher step frequency, shorter contact time and longer stride length compared to lower-level athletes.

Materials & Methods

Sixteen female athletes, 8 national champions of track and field (Mean $\pm$ SD: age 21.5 ± 2.07 years; stature 1.71 ± 0.10 m; weight 62.35 ± 7.27 kg) and 8 lower-level track and field athletes (age 20.0 ± 3.21 years; stature 1.73 ± 0.05 m; weight 60.06 ± 4.77 kg) participated in the study. Among high level there were -2- 100m sprinters (personal best = 11.90 ± 0.2 s), 1 pole vaulter (personal best = 4.71 m), 1 high-jumper (personal best = 1.94 m), 2 200m sprinters (personal best = 25.36 ± 0.2 s), 1 400m sprinter (personal best = 56.22 s), 1 100m hurdles (personal best = 14.11 s). Ethical approval was gained from the Institutional Research Ethics Committee, and each participant provided written informed consent before commencement of the study.

The session began with a sprint-specific warm-up that involved a 10 min of jogging, 5 min of lower limb muscle dynamic stretching, 5 min of sprint-specific drills and three progressive runs over 40 m, separated by 2 min of passive rest (Jiménez-Reyes et al., 2019). Following the warm-up, each athlete performed two maximal 30m sprints in a stadium with a synthetic track with 5-6 min rest between each trial. Participants initiated each sprint attempt adopting a 3-point starting position with the hand behind the start line (Romero-Franco et al., 2017; Samozino et al., 2016).

The full sprint distance was recorded using three high-speed panning cameras (Casio EX-FX1, Casio Computer Co. Ltd, Shibuya, Japan) operating at a sampling frequency of 300 fps and their settings proposed by Pueo (Pueo, 2016). The cameras were placed perpendicular to the running direction (at 5, 15 and 25 m) and fixed on stable tripods 10m away from the running lane. Each camera was used to capture data for 10m intervals (Cronin et al., 2008). To determine the 5m split times, marking poles were placed along the 30m distance, correcting video parallax error (Romero-Franco et al., 2017) (Figure 1). Moreover, pairs of 0.05 m $\times$ 0.05 m custom reference markers were placed on both sides of the entire runway for the extraction of step length. The placement of the markers formed one-meter zones along the running lane. The conduction of the panning analysis was consistent according to previous recommendations (Chow, 1993; Gervais et al., 1989). The faster trial, based on 30m sprint time, was used in further analysis.

Figure 1. Experimental set up

Data analysis

The video data were analyzed using Quintic Biomechanics software (v31) (Quintic Consultancy Ltd, Birmingham, UK). Temporal analysis of the video recording of each camera was performed to identify the split times for every 5m interval. The first propulsive movement of the rear leg was set as the starting point. Then, split times were defined as the frame in which athletes' hips crossed the marking poles, where 5m split time and running speed were calculated for each interval (Romero-Franco et al., 2017; Samozino et al., 2016).

Kinematic analysis was also performed on the frames containing the instance of touchdown and take-off in each step. Touchdown was defined as the instant at which the foot contacted the ground and take-off as the instant at which the foot left the ground (Paradisis & Cooke, 2006). The appropriate frames defining touchdown and take-off were identified through visual inspection by the researcher who analyzed all the trials (Paradisis & Cooke, 2001). Ground contact time was calculated as the time that the foot was in contact with the ground and flight time as the time from take-off of the ipsilateral foot to touchdown of the contralateral foot. Step length was determined as the difference in anteroposterior position of the toes between two consecutive steps (Chow, 1993). The distance from the toe to the custom reference markers was calculated by projecting the point of the athlete's toe at touchdown onto a line between pairs of markers (Chow, 1993; Gervais et al., 1989; Hay & Koh, 1988). Furthermore, the step length was expressed relative to the stature. Finally, step frequency was calculated by dividing running speed by step length. All analyzed parameters were presented as the average per 5-m splits. The high reliability and validity of the analysis with reference markers to determine sprint kinematics by panning cameras has been reported elsewhere (Nagahara et al., 2014; Panoutsakopoulos et al., 2020).

The entire F-v relationship represents the maximal theoretical horizontal force that the lower limbs could produce over one contact at a null velocity (F_0) and the theoretical maximum velocity that could be produced during a support phase in the absence of mechanical constraints (V_0). These variables were calculated as extrapolated from the linear sprint F-v relationship. Multiplying horizontal F and v values for each support phase, the equivalent of theoretical maximal mechanical power output in the forward direction is obtained and computed as $P_{max} = F_0 \times V_0 / 4$. Additionally, RF was calculated as the ratio of the horizontally oriented force to the total force and DRF was computed as the slope of the linear RF-v relationship, as the velocity increases (Morin et al., 2019; Samozino et al., 2016). The sprint-velocity time per 5-m interval was determined from the modelled velocity-time data of each camera.

Statistical analysis

Data are presented as means $\pm$ standard deviation (SD) with 95% confidence intervals (CI). Independent samples t-tests were used to compare the sprint mechanical and kinematic variables, between the NC and LL competitors. The magnitude of the differences was also expressed using Cohen's d measure of effect size (ES). The criteria to interpret the magnitude of the ES was as follows: small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$). (Cohen, 1992) All statistical analyses were performed using the software package SPSS (IBM SPSS version 25.0, Chicago, IL, USA), and statistical significance was set at an alpha level of 0.05.

Results

The group data of the sprint mechanical profiles are shown in Table 1.

Table1. Mean $\pm$ SD, 95% CI and between-group inferential statistics for sprinting mechanical parameters for the two groups.

Variable	Group	Mean $\pm$ SD	95% CI	t	p	Cohen's d
F_0 (N $\cdot$ kg ⁻¹)	NC	7.14 $\pm$ 0.61	6.62, 7.65	1.027	0.322	0.07
	LL	6.79 $\pm$ 0.72	6.79, 6.18			
V_0 (m $\cdot$ s ⁻¹)	NC	9.35 $\pm$ 0.31	9.09, 9.61	6.271**	0.000	0.15
	LL	8.44 $\pm$ 0.27	8.21, 8.66			
P_{max} (W $\cdot$ kg ⁻¹)	NC	16.66 $\pm$ 1.22	15.64, 17.68	3.262**	0.006	0.23
	LL	14.32 $\pm$ 1.62	12.97, 15.67			
RF (%)	NC	44 $\pm$ 2	43, 45	2.576*	0.022	0.09
	LL	41 $\pm$ 2	40, 43			
DRF (% $\cdot$ s $\cdot$ m)	NC	-7 $\pm$ 1	-8, -6	<0.917	>0.375	0.09
	LL	-8 $\pm$ 1	-8, -7			

Note: F_0 = theoretical maximal horizontal force; v_0 = theoretical maximal horizontal velocity; P_{max} = theoretical maximal horizontal power; RF = ratio of horizontal force to total ground reaction force; DRF = decrease in RF with increasing speed; NC =National-champions; LL= Low-level. * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

There were significant between-group differences for P_{max} ($t = 3.262$, $p = 0.006$, $d = 0.23$) and V_0 ($t = 6.271$, $p = 0.000$, $d = 0.15$) (figure 2). RF_{max} was also higher in the National Champions ($t = 2.576$, $p = 0.022$, $d = 0.09$). There were no between-group differences for F_0 ($t = 1.027$, $p = 0.322$, $d = 0.07$) or DRF ($t < 0.917$, $p > 0.375$, $d = 0.09$).

Figure 2. Graphic representation of the relationship between force-velocity and power-velocity as profiled from the average values of a 30-m sprint testing procedure between high-level (black line) and low-level female athletes (dashed line). F_0 and V_0 represent the y and x intercepts of the linear regression, and the theoretical maximum of force, and velocity able to be produced in the absence of their opposing unit. P_{max} represents the maximum power produced, determined as the peak of the polynomial fit between power and velocity.

No differences were found between the two-level groups in the mean step length, relative step length and flight time in the intervals (0-5, 5-10, 10-15, 15-20, 20-25, and 25-30 m) while the mean running velocity and step frequency was higher for the NC in all but one (0-5 m) 5-m distance intervals of the 30-m sprint (Figure 3). Also, the mean contact time was higher for the NC in the intervals (5-10, 10-15, 15-20 and 20-25). The descriptive data of the kinematic characteristics seems in Tables 2 and 3.

Table 2. Mean $\pm$ SD, 95% CI and between-group inferential statistics for sprinting mean velocity, step length and relative step length.

	Distance (m)	Group	Mean $\pm$ SD	95% CI	t	p	Cohen's d
Mean velocity (m/s)	0-5	NC	3.62 $\pm$ 0.15	3.49, 3.74	2.299	0.037	0.07
		LL	3.45 $\pm$ 0.14	3.33, 3.57			
	5-10	NC	6.76 $\pm$ 0.18	6.61, 6.90	3.801**	0.002	0.08
		LL	6.39 $\pm$ 0.21	6.22, 6.57			
	10-15	NC	7.70 $\pm$ 0.12	7.59, 7.80	6.215***	0.000	0.11
		LL	7.15 $\pm$ 0.22	6.97, 7.33			
	15-20	NC	8.20 $\pm$ 0.12	8.10, 8.30	6.074***	0.000	0.11
		LL	7.62 $\pm$ 0.24	7.42, 7.82			
	20-25	NC	8.49 $\pm$ 0.29	8.33, 8.65	7.093***	0.000	0.13
		LL	7.79 $\pm$ 0.21	8.61, 7.96			
	25-30	NC	8.65 $\pm$ 0.24	7.45, 8.85	5.919***	0.000	0.13
		LL	7.92 $\pm$ 0.25	7.71, 8.13			
Step length (m)	0-5	NC	1.20 $\pm$ 0.17	1.06, 1.34	0.357	0.726	0.03
		LL	1.18 $\pm$ 0.08	1.11, 1.24			
	5-10	NC	1.54 $\pm$ 0.06	1.49, 1.60	0.000	1.00	0.00
		LL	1.54 $\pm$ 0.07	1.48, 1.60			
	10-15	NC	1.72 $\pm$ 0.07	1.66, 1.78	-0.435	0.670	0.01
		LL	1.73 $\pm$ 0.04	1.70, 1.77			
	15-20	NC	1.82 $\pm$ 0.09	1.75, 1.93	0.131	0.898	0.00
		LL	1.82 $\pm$ 0.09	1.74, 1.90			
	20-25	NC	1.91 $\pm$ 0.07	1.76, 1.87	0.681	0.507	0.02
		LL	1.89 $\pm$ 0.06	1.86, 1.98			
	25-30	NC	1.97 $\pm$ 0.10	1.84, 1.94	0.331	0.745	0.01
		LL	1.95 $\pm$ 0.08	1.88, 2.05			
Relative step length	0-5	NC	0.71 $\pm$ 0.11	0.61, 0.79	0.514	0.615	0.04
		LL	0.68 $\pm$ 0.04	0.65, 0.71			
	5-10	NC	0.90 $\pm$ 0.04	0.87, 0.93	0.613	0.550	0.01
		LL	0.89 $\pm$ 0.04	0.86, 0.91			
	10-15	NC	1.00 $\pm$ 0.05	0.97, 1.05	0.412	0.687	0.00
		LL	1.00 $\pm$ 0.02	0.98, 1.03			
	15-20	NC	1.06 $\pm$ 0.05	1.02, 1.10	0.131	0.898	0.01
		LL	1.05 $\pm$ 0.03	1.03, 1.07			
	20-25	NC	1.12 $\pm$ 0.06	1.07, 1.18	1.044	0.314	0.03
		LL	1.10 $\pm$ 0.03	1.06, 1.12			
	25-30	NC	1.15 $\pm$ 0.06	1.07, 1.12	0.745	0.469	0.02
		LL	1.13 $\pm$ 0.03	1.11, 1.15			

Note: NC = National female Champions; LL= Low-level female athletes. * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

Table 3. Mean $\pm$ SD, 95% CI and between-group inferential statistics for sprinting mean contact time, flight time and step frequency.

	Distance (m)	Group	Mean $\pm$ SD	95% CI	t	p	Cohen's d
Contact time (s)	0-5	NC	0.180 $\pm$ 0.027	0.157, 0.202	-0.351	0.731	0.02
		LL	0.183 $\pm$ 0.014	0.172, 0.196			
	5-10	NC	0.132 $\pm$ 0.013	0.120, 0.144	-2.226*	0.043	0.10
		LL	0.146 $\pm$ 0.010	0.137, 0.155			
	10-15	NC	0.122 $\pm$ 0.008	0.115, 0.129	-2.496*	0.026	0.12
		LL	0.133 $\pm$ 0.009	0.126, 0.141			
	15-20	NC	0.116 $\pm$ 0.010	0.107, 0.125	-2.302*	0.037	0.11
		LL	0.127 $\pm$ 0.008	0.120, 0.135			
	20-25	NC	0.112 $\pm$ 0.011	0.103, 0.122	-2.469*	0.027	0.13
		LL	0.126 $\pm$ 0.010	0.117, 0.135			
Flight time (s)	0-5	NC	0.112 $\pm$ 0.012	0.103, 0.122	-2.075	0.057	0.13
		LL	0.122 $\pm$ 0.007	0.116, 0.128			
	5-10	NC	0.078 $\pm$ 0.016	0.078, 0.065	0.293	0.774	0.07
		LL	0.076 $\pm$ 0.017	0.061, 0.091			
	10-15	NC	0.095 $\pm$ 0.007	0.095, 0.088	0.000	1.000	-0.01
		LL	0.095 $\pm$ 0.005	0.090, 0.099			
	15-20	NC	0.108 $\pm$ 0.004	0.105, 0.112	0.000	1.000	-0.03
		LL	0.108 $\pm$ 0.008	0.102, 0.116			
	20-25	NC	0.110 $\pm$ 0.005	0.105, 0.115	-0.357	0.727	0.04
		LL	0.111 $\pm$ 0.008	0.104, 0.118			
Step frequency (Hz)	0-5	NC	0.116 $\pm$ 0.005	0.112, 0.121	-0.509	0.619	0.00
		LL	0.111 $\pm$ 0.004	0.113, 0.121			
	5-10	NC	0.121 $\pm$ 0.006	0.116, 0.125	0.424	0.678	0.00
		LL	0.117 $\pm$ 0.007	0.115, 0.124			
	10-15	NC	2.87 $\pm$ 0.38	2.55, 3.18	-0.340	0.739	0.02
		LL	2.92 $\pm$ 0.19	2.76, 3.08			
	15-20	NC	4.38 $\pm$ 0.21	4.20, 4.56	2.686*	0.018	0.08
		LL	4.15 $\pm$ 0.10	4.06, 4.23			
	20-25	NC	4.42 $\pm$ 0.24	4.22, 4.62	3.434**	0.004	0.11
		LL	4.12 $\pm$ 0.09	4.04, 4.19			

Note: NC= National female champions; LL= Low-level female athletes * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

Figure 3. Graphical representation of mean step length (continuous line) and mean step frequency (dashed line) during a sprint testing procedure for low-level (above) and high-level (below) female athletes.

Discussion

The present study explored the mechanical and kinematic differences at the acceleration phase at a straight-line 30 m sprint between high-level and low-level female track and field athletes. Our first hypothesis, which stated that the faster-sprinting athletes compared to slower athletes would produce superior mechanical characteristics, is verified. On the contrary, no differences were found between groups for step length (SL), step length relative (SLR) and flight time (FT) while step frequency (SF) was higher and mean contact time (CT) were shorter for the National champions. The above support our second hypothesis that these kinematics factors are higher in faster female athletes.

The results of the research showed that there were no significant differences in horizontal Force (F_0) at low velocities between high-level and low-level female athletes which mean that they produced similar horizontal force in the first slow steps of the sprint. However, significant differences were observed for two primary mechanical variable (V_0 , P_{max}) and the proportion of the force applied horizontally (RF_{max}), with a high-level group demonstrating a mechanical advantage, something that partially explains the difference in the performance level between these groups. Specifically, the theoretical maximal velocity (V_0) shows that high-level female athletes can develop higher maximal velocity and keep producing horizontal force at higher velocities, which reflects a higher capability of lower limb to produce horizontal force at fast running speeds. This is also reflected in the fact that high-level female athletes have higher overall mechanical power output capabilities (P_{max}) during the acceleration phase than low-level female athletes. In addition, the ratio of force (RF) was higher which means that high-level female athletes can apply more effectively the force developed by the lower limbs at low velocities. The ratio of force (RF) corresponds to the ability to orient the horizontal force effectively at low velocities in the first steps of the acceleration phase in relation to the total force produced. Nevertheless, the ability to maintain high level of effectiveness despite the increase in velocity (DRF) was not different between high and low level athletes. The capability to keep developing horizontal force at very high velocities than the capability to produce very high level of horizontal force at low ones seems to be the main mechanical characteristic that affects the performance in speed in high level female athletes. These results are in agreement with previous studies that have revealed that high level athletes are able to horizontally apply higher forces upon contact with the ground (Jiménez-Reyes et al., 2018; Kawamori et al., 2014; Morin et al., 2011).

The present kinematic data revealed significant differences for mean velocity values in all but one distance interval (even though p value in the 0-5 m interval was 0.050) between the high-level and lower-level female athletes, an observation in agreement with the results of V_0 . As expected, running velocity is a variable that clearly discriminates sprinters and other athletes in power events between different performance levels. The results of this study are in line with previous study which has indicated that high-level male sprinters are able to produce higher maximal running velocities in the 35-m distance compared medium-level sprinters (Paradisis et al., 2019).

In terms of mean SL, SLR and FT the present investigation indicated no significant differences between the two groups whilst the mean SF is significant higher in the national-champions athletes. These results are in partial agreement with previous studies which have shown that better sprinters show higher values of step frequencies (Lieberman et al., 2015; Slawinski & Billat, 2004; Paradisis et al., 2019). According to the above, we would consider higher-level sprinters to keep more their neural system readier for fast leg turnover than lower-level sprinters (Salo et al., 2011). Therefore, we can assume that the current relative differences between the two female groups in step frequency fall within an expected region for their performance levels. Furthermore, CT was shorter in all but two (0-5 m, 25-30m) 5-m distance intervals of the 30-m sprint confirming the principle that higher running speeds are achieved through lower contact times and faster sprinters spent less time in contact with the ground (Morin et al., 2012; Paradisis & Cooke, 2006; Weyand et al., 2000, 2010).

As we expected the variables of sprint mechanical profile and kinematic characteristics were greater in high-level female athletes than in low ones consequently and the speed was higher in faster female athletes as well. The faster athletes in our study could keep more developing more horizontal force at very high velocities, apply more effectively the force produced at low velocities in the first steps of the acceleration phase, spend less time in contact with the ground and show higher values of SF than slower athletes ones. This supports the suggestion that the faster sprinters had improved the neural and/or the contractile characteristics, probably due to years of training. Therefore, in our study, low-level female athletes should focus on the increase of V_0 through appropriate training, which include technical drills, long accelerations (20-50m) and horizontal plyometrics (Morin & Samozino, 2018).

To our knowledge, this is the only study exploring the differences in sprint mechanics and kinematics between National female champions of track and field events and lower-level competitors. The sprint mechanical profile thought-provoking since it carries information about what causes performance fluctuation. Consequently, it is expected to be useful for both researchers and coaches to designed better training programs focused on improving the horizontal components of F-v profile. Future research should investigate further the kinematics parameters to better understand their contribution to acceleration relative to sprint mechanics to design effective training programs. The study has some limitations that must be addressed. The sample of the current study includes athletes from different power events of track and field (pole vault, high jump, sprint 100-400m and

100m hurdles) with different technical characteristics therefore there are differences in the ability to apply the force into the anteroposterior direction (Stavridis et al., 2019). Moreover, we believe that the variables of the F-v and P-v mechanical profile were not affected by the methods used, since they agreed with other studies evaluating the same parameters (Haugen et al., 2019; Jiménez-Reyes et al., 2018, 2019; Romero-Franco et al., 2017; Stavridis et al., 2019, 2020).

Conclusion

The main findings of the present study were that the high-level track and field female athletes can keep developing horizontal forces at very high velocities and orient effectively the force onto the ground during acceleration phase than the lower-level female competitors. Concerning the kinematic characteristics there were significant differences at mean CT and SF between high-level and lower-level female athletes. Therefore, the sprint mechanical profiles in combination with kinematics characteristics affect the sprinting performance. Consequently, the training participants must focus on exercises targeting kinematic (CT, LS) and kinetic (Horizontal Force and power) variables. The practical applications of the present study support that the sprint mechanical F-v profile is useful method for coaches to ensure an accurate characterization of female athletes' physical qualities to design effective training programs toward to performance maximization.

Conflicts of interest

The authors have no conflicts of interest to declare.

References

- Alcazar, J., Rodriguez-Lopez, C., Ara, I., Alfaro-Acha, A., Rodríguez-Gómez, I., Navarro-Cruz, R., Losa-Reyna, J., García-García, F. J., & Alegre, L. M. (2018). Force-velocity profiling in older adults: An adequate tool for the management of functional trajectories with aging. *Experimental Gerontology*, 108, 1–6. <https://doi.org/10.1016/j.exger.2018.03.015>
- Brughelli, M., Cronin, J., & Chaouachi, A. (2011). Effects of Running Velocity on Running Kinetics and Kinematics. *Journal of Strength and Conditioning Research*, 25(4), 933–939. <https://doi.org/10.1519/JSC.0b013e3181c64308>
- Chow, J. W. (1993). A Panning Videographic Technique to Obtain Selected Kinematic Characteristics of the Strides in Sprint Hurdling. *Journal of Applied Biomechanics*, 9(2), 149–159. <https://doi.org/10.1123/jab.9.2.149>
- Cohen, J. (1992). Statistical Power Analysis. *Current Directions in Psychological Science*, 1(3), 98–101. <https://doi.org/10.1111/1467-8721.ep10768783>
- Cronin, J., Hansen, K., Kawamori, N., & McNair, P. (2008). Effects of weighted vests and sled towing on sprint kinematics. *Sports Biomechanics*, 7(2), 160–172. <https://doi.org/10.1080/14763140701841381>
- Cross, M. R., Brughelli, M., Brown, S. R., Samozino, P., Gill, N. D., Cronin, J. B., & Morin, J. B. (2015). Mechanical Properties of Sprinting in Elite Rugby Union and Rugby League. *International Journal of Sports Physiology and Performance*, 10(6), 695–702. <https://doi.org/10.1123/ijspp.2014-0151>
- Debaere, S., Delecluse, C., Aerenhouts, D., Hagman, F., & Jonkers, I. (2013). From block clearance to sprint running: Characteristics underlying an effective transition. *Journal of Sports Sciences*, 31(2), 137–149. <https://doi.org/10.1080/02640414.2012.722225>
- Gervais, P., Bedingfield, E. W., Wronko, C., Kollias, I., Marchiori, G., Kuntz, J., Way, N., & Kuiper, D. (1989). Kinematic measurement from panned cinematography. *Canadian Journal of Sport Sciences = Journal Canadien Des Sciences Du Sport*, 14(2), 107–111. <https://psycnet.apa.org/record/1989-38732-001>
- Gleadhill, S., & Nagahara, R. (2021). Kinetic and kinematic determinants of female sprint performance. *Journal of Sports Sciences*, 39(6), 609–617. <https://doi.org/10.1080/02640414.2020.1837449>
- Haugen, T. A., Breitschädel, F., & Seiler, S. (2019). Sprint mechanical variables in elite athletes: Are force-velocity profiles sport specific or individual? *PloS One*, 14(7), e0215551. <https://doi.org/10.1371/journal.pone.0215551>
- Hay, J. G., & Koh, T. J. (2016). Evaluating the Approach in the Horizontal Jumps. *International Journal of Sport Biomechanics*, 4(4), 372–392. <https://doi.org/10.1123/ijsb.4.4.372>
- Hunter, A. P., Marshall, R. N., & McNair, P. J. (2004). Interaction of Step Length and Step Rate during Sprint Running. *Med. Sci. Sports Exerc*, 36(2), 261–271. <https://doi.org/10.1249/01.MSS.0000113664.15777.53>
- Jiménez-Reyes, P., García-Ramos, A., Cuadrado-Peñañiel, V., Párraga-Montilla, J. A., Morcillo-Losa, J. A., Samozino, P., & Morin, J. B. (2019). Differences in Sprint Mechanical Force-Velocity Profile Between Trained Soccer and Futsal Players. *International Journal of Sports Physiology and Performance*, 14(4), 478–485. <https://doi.org/10.1123/ijspp.2018-0402>
- Jiménez-Reyes, P., Samozino, P., García-Ramos, A., Cuadrado-Peñañiel, V., Brughelli, M., & Morin, J.B. (2018). Relationship between vertical and horizontal force-velocity-power profiles in various sports and levels of practice. *PeerJ*, 6(11), e5937. <https://doi.org/10.7717/peerj.5937>
- Kawamori, N., Newton, R., & Nosaka, K. (2014). Effects of weighted sled towing on ground reaction force

- during the acceleration phase of sprint running. *Journal of Sports Sciences*, 32(12), 1139–1145. <https://doi.org/10.1080/02640414.2014.886129>
- Lieberman, D. E., Warrener, A. G., Wang, J., & Castillo, E. R. (2015). Effects of stride frequency and foot position at landing on braking force, hip torque, impact peak force and the metabolic cost of running in humans. *Journal of Experimental Biology*, 218(21), 3406–3414. <https://doi.org/10.1242/jeb.125500>
- Mirkov, D. M., Knezevic, O. M., Garcia-Ramos, A., Čoh, M., & Šarabon, N. (2020). Gender-related differences in mechanics of the sprint start and sprint acceleration of top national-level sprinters. *International Journal of Environmental Research and Public Health*, 17(18), 1–11. <https://doi.org/10.3390/ijerph17186447>
- Morin, J. B., Edouard, P., & Samozino, P. (2011). Technical ability of force application as a determinant factor of sprint performance. *Medicine and science in Sports and Exercise*, 43(9), 1680–1688. <https://doi.org/10.1249/MSS.0b013e318216ea37>
- Morin, J. B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P., & Lacour, J. R. (2012). Mechanical determinants of 100-m sprint running performance. *European Journal of Applied Physiology*, 112(11), 3921–3930. <https://doi.org/10.1007/s00421-012-2379-8>
- Morin, J. B., & Samozino, P. (2016). Interpreting Power-Force-Velocity Profiles for Individualized and Specific Training. *International Journal of Sports Physiology and Performance*, 11(2), 267–272. <https://doi.org/10.1123/ijssp.2015-0638>
- Morin, J. B., & Samozino, P. (2018). Biomechanics of Training and Testing. In J. B. Morin & P. Samozino (Eds.), *Biomechanics of Training and Testing: Innovative Concepts and Simple Field Methods*. New York, NY: Springer International Publishing. <https://doi.org/10.1007/978-3-319-05633-3>
- Morin, J. B., Samozino, P., Murata, M., Cross, M. R., & Nagahara, R. (2019). A simple method for computing sprint acceleration kinetics from running velocity data: Replication study with improved design. *Journal of Biomechanics*, 94, 82–87. <https://doi.org/10.1016/j.jbiomech.2019.07.020>
- Nagahara, R., Naito, H., Morin, J. B., & Zushi, K. (2014). Association of acceleration with spatiotemporal variables in maximal sprinting. *International Journal of Sports Medicine*, 35(9), 755–761. <https://doi.org/10.1055/s-0033-1363252>
- Nagahara, R., & Girard, O. (2021). Alterations of spatiotemporal and ground reaction force variables during decelerated sprinting. *Scandinavian Journal of Medicine & Science in Sports*, 31(3), 586–596. <https://doi.org/10.1111/sms.13884>
- Nagahara, R., Mizutani, M., Matsuo, A., Kanehisa, H., & Fukunaga, T. (2018). Step-to-step spatiotemporal variables and ground reaction forces of intra-individual fastest sprinting in a single session. *Journal of Sports Sciences*, 36(12), 1392–1401. <https://doi.org/10.1080/02640414.2017.1389101>
- Panoutsakopoulos, V., Theodorou, A. S., Kotzamanidou, M. C., Fragkoulis, E., Smirniotou, A., & Kollias, I. A. (2020). Gender and event specificity differences in kinematical parameters of a 60 m hurdles race. *International Journal of Performance Analysis in Sport*, 20(4), 668–682. <https://doi.org/10.1080/24748668.2020.1776064>
- Paradisis, G., Bissas, A., Pappas, P., Zacharogiannis, E., Theodorou, A., & Girard, O. (2019). Sprint mechanical differences at maximal running speed: Effects of performance level. *Journal of Sports Sciences*, 37(17), 2026–2036. <https://doi.org/10.1080/02640414.2019.1616958>
- Paradisis, Giorgos P., & Cooke, C. (2001). Kinematic and postural characteristics of sprint running on sloping surfaces. *Journal of Sports Sciences*, 19(2), 149–159. <https://doi.org/10.1080/026404101300036370>
- Paradisis, G., & Cooke, C. (2006). The effects of sprint running training on sloping surfaces. *Journal of Strength and Conditioning Research*, 20(4), 767–777. <https://doi.org/10.1519/R-16834.1>
- Pueo, B. (2016). High speed cameras for motion analysis in sports science. *Journal of Human Sport and Exercise*, 11(1). <https://doi.org/10.14198/jhse.2016.111.05>
- Romero-Franco, N., Jiménez-Reyes, P., Castaño-Zambudio, A., Capelo-Ramírez, F., Rodríguez-Juan, J. J., González-Hernández, J., Toscano-Bendala, F. J., Cuadrado-Peñafiel, V., & Balsalobre-Fernández, C. (2017). Sprint performance and mechanical outputs computed with an iPhone app: Comparison with existing reference methods. *European Journal of Sport Science*, 17(4), 386–392. <https://doi.org/10.1080/17461391.2016.1249031>
- Salo, A. I., Bezodis, I., Batterham, A., & Kerwin, D. (2011). Elite sprinting: are athletes individually step-frequency or step-length reliant? *Medicine and Science in Sports and Exercise*, 43(6), 1055–1062. <https://doi.org/10.1249/MSS.0b013e318201f6f8>
- Samozino, P., Rabita, G., Dorel, S., Slawinski, J., Peyrot, N., Saez de Villarreal, E., & Morin, J. B. (2016). A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. *Scandinavian Journal of Medicine & Science in Sports*, 26(6), 648–658. <https://doi.org/10.1111/sms.12490>
- Slawinski, J., Termoz, N., Rabita, G., Guilhem, G., Dorel, S., Morin, J. B., & Samozino, P. (2017). How 100-m event analyses improve our understanding of world-class men's and women's sprint performance. *Scandinavian Journal of Medicine & Science in Sports*, 27(1), 45–54. <https://doi.org/10.1111/sms.12627>
- Slawinski, J., & Billat, V. L. (2004). Difference in mechanical and energy cost between highly, well, and

- nontrained runners. *Medicine and Science in Sports and Exercise*, 36(8), 1440–1446.
<https://doi.org/10.1249/01.MSS.0000135785.68760.96>
- Stavridis, I., Smilios, I., Tsopanidou, A., Economou, T., & Paradisis, G. (2019). Differences in the Force Velocity Mechanical Profile and the Effectiveness of Force Application During Sprint-Acceleration Between Sprinters and Hurdlers. *Frontiers in Sports and Active Living*, 1.
<https://doi.org/10.3389/fspor.2019.00026>
- Stavridis, I., Tsopanidou, A., Tsolakis, C., Zacharogiannis, E., Koulouvaris, P., & Paradisis, G. (2020). Force-Velocity Relationship Between Sprinting and Jumping Testing Procedures. *ISBS Proceedings Archive*, 38(1), 12.
- Weyand, P. G., Sandell, R. F., Prime, D. N. L., & Bundle, M. W. (2010). The biological limits to running speed are imposed from the ground up. *Journal of Applied Physiology*, 108(4), 950–961.
<https://doi.org/10.1152/jappphysiol.00947.2009>
- Weyand, P. G., Sternlight, D. B., Bellizzi, M. J., & Wright, S. (2000). Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *Journal of Applied Physiology (Bethesda, Md. : 1985)*, 89(5), 1991–1999. <https://doi.org/10.1152/jappl.2000.89.5.1991>