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Sprint mechanics in world-class athletes: a new insight into the limits of human locomotion

G. Rabita[1], S. Dorel[2], J. Slawinski[3], E. Sàez-de-Villarreal[4], A. Couturier[1], P. Samozino[5], J-B. Morin[6]

[1]Research Department, National Institute of Sport, INSEP, Paris, France, [2]Laboratory "Movement, Interactions, Performance" (EA 4334), University of Nantes, Nantes, France, [3]Research Center in Sport and Movement (EA 2931), University of Paris Ouest Nanterre La Défense, Paris, France, [4]Faculty of Sports, University Pablo de Olavide, Seville, Spain, [5]Laboratory of Exercise Physiology (EA 4338), University of Savoie, Le Bourget-du-Lac, France, [6]Laboratory of Human Motricity, Education Sport and Health (EA 6309), University of Nice Sophia Antipolis, Nice, France

Corresponding author: Giuseppe Rabita, PhD, Research Department, National Institute of Sport, INSEP, 11 Avenue du Tremblay, 75012 Paris, France. Tel: +33 (0)1 41 74 44 71, Fax: +33 (0)1 41 74 43 35, E-mail: giuseppe.rabita@insep.fr

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The objective of this study was to characterize the mechanics of maximal running sprint acceleration in high-level athletes. Four elite (100-m best time 9.95–10.29 s) and five sub-elite (10.40–10.60 s) sprinters performed seven sprints in overground conditions. A single virtual 40-m sprint was reconstructed and kinetics parameters were calculated for each step using a force platform system and video analyses. Anteroposterior force (F_Y), power (P_Y), and the ratio of the horizontal force component to the resultant (total) force (RF, which reflects the orientation of the resultant ground reaction force for each support phase) were computed as a function of velocity (V). F_Y-V, RF-V, and P_Y-V relationships were well described by significant linear (mean R^2 of 0.892 ± 0.049 and 0.950 ± 0.023) and quadratic (mean $R^2 = 0.732 \pm 0.114$) models, respectively. The current study allows a better understanding of the mechanics of the sprint acceleration notably by modeling the relationships between the forward velocity and the main mechanical key variables of the sprint. As these findings partly concern world-class sprinters tested in overground conditions, they give new insights into some aspects of the biomechanical limits of human locomotion.

Elite athletes specialized in the short sprint (60 or 100 m) constitute a unique model to investigate some aspects of human limits (Denny, 2008). Their specific muscular, physiological, and biomechanical features have frequently been investigated as they are considered the fastest human runners on Earth (Ben Sira et al., 2010; Slawinski et al., 2010). Regarding world-class sprinters in particular, their 100-m race characteristics have been systematically described in official events such as World Championships or summer Olympic Games (Taylor & Beneke, 2012; Krzysztof & Mero, 2013). Such an approach has the obvious advantage of allowing the characterization of the best 100-m performance ever and the few fastest men who present at the given time an extreme motivation and theoretically optimal technique and physical shape. In return, because of the constraints inherent to such international events, these conditions usually have the drawback of allowing the measurement or estimation of only a few basic variables [e.g., forward velocity, flight time, and contact time (Taylor & Beneke, 2012) or step length and step frequency (Krzysztof & Mero, 2013)] from video footage generally provided by television stations.

When considering elite athletes, the lack of experimental data still prevents us from thoroughly understanding the determinants of sprint performance (Morin et al., 2012). Recent experimental measures have been previously reported, but analyses have generally focused either around a single mark of the sprint distance during acceleration [e.g., starting phase (Slawinski et al., 2010; Debaere et al., 2013a; Kawamori et al., 2014; Otsuka et al., 2014), the 8-m mark (Kawamori et al., 2013), the 16-m mark (Hunter et al., 2004), the 45-m mark (Bezodis et al., 2008)] or on the constant-maximal speed phase of the sprint (Weyand et al., 2000, 2010; Bergamini et al., 2012). Thus, it would be of great interest to have the opportunity to describe from a mechanical standpoint the sprint acceleration phase: in particular, this would allow the characterization of (a) individual force–velocity (F-V) and power–velocity (P-V) relationships and (b) key variables of the sprint technique.

Numerous studies have investigated the F-V relationships in functional tasks (Rahmani et al., 2001; Samozino et al., 2010). Classically, the following theoretical parameters have been derived from the linear F-V relationships: (a) the maximal velocity (V0) calculated by extrapolation to zero force; (b) the maximal force (F0) calculated by extrapolation to zero velocity; and (c) the maximal power output (P_{max}), maximal value of the product of F and V variables. Regarding the sprint running task in particular, experimental investigations have been developed using instrumented treadmills to perform measurements throughout the entire acceleration phase. The subject's forward velocity was given by the speed of the belt and the anteroposterior force production can be directly obtained by force sensors positioned under the motorized treadmill frame (Morin et al., 2010). Characterizing F-V relationships by means of such methodologies allows to assess the ability of the neuromuscular system to generate maximal power. This ability, influenced by interrelated factors [e.g., muscle fiber composition, architectural characteristics, anatomical joint configuration, levels of neural activation, and technical aspects (for review, see Cormie et al., 2011)], was shown to be correlated with sprint performance (Morin et al., 2012) as previously demonstrated in other sport activities (Dorel et al., 2005, 2010). Moreover, it helps determine the individual mechanical profile of the athlete in his specific sprint running task (Morin et al., 2012).

On the other hand, the measurement of the ground reaction force (GRF) for each step of the acceleration phase allows not only to quantify the horizontal component of this GRF but also its contribution to the total GRF. Indeed, previous investigations (Morin et al., 2011; 2012), by transposing the concept of effectiveness used in pedaling mechanics, calculated the ratio of force (RF) during treadmill sprint running. This RF parameter reflects the orientation of the resultant GRF at each step and then the athletes' ability to apply force effectively onto the ground (i.e., in the forward direction). Interestingly, these authors showed that the mean RF parameter obtained on the treadmill was highly correlated to the track 100-m performance. They also proposed an index of force application technique (D_{RF}) computed as the slope of the linear RF-horizontal velocity relationship from sprint start until top speed. This D_{RF} parameter reflects the capability to limit the systematic decrease in RF as speed increases. In other words, it reveals the athlete's aptitude to maintain an efficient sprint technique despite increasing speed. D_{RF} has also been shown to be highly related to 100-m performance (Morin et al., 2011, 2012). Noticeably, these studies also highlighted that the resultant GRF produced over sprint acceleration was not correlated to sprint performance.

The above-mentioned literature shows that the use of F-V, P-V, and RF-V relationships because of the close link between their associated variables and field performance have undoubtedly contributed to a better understanding of the mechanical determinants of sprint running; however, they have only been recorded and studied in sprint treadmill conditions. Consequently, even if these data were collected in elite athletes (Morin et al., 2012), this limitation prevents real and definitive insights into the human determinants of sprint acceleration performance. Firstly, in treadmill conditions, subjects started in a crouched position instead of using starting blocks, which is a substantial issue considering the importance of this phase in 60- and 100-m performance (Harland & Steele, 1997; Slawinski et al., 2010). Secondly, the maximal velocities reached by the athletes on the treadmill were substantially lower than those recorded in overground conditions (Morin et al., 2012). For example, Chelly and Denis (2001) and Morin et al. (2012) measured maximal treadmill velocity around 6.5 and 7.5 m/s, respectively, which is far from the maximal speed reached by elite sprinters during field sprints (e.g., 12.5 m/s for Usain Bolt's 100-m World Record).

In the present study, we had the unique opportunity to study the mechanical determinants of sprint performance in nine high-level sprinters, including four world-class athletes (among them was the 2013 60-m indoor European champion in Göteborg, Sweden, see Materials and methods section). The second main originality of this study was that the acceleration phase was studied for the first time in field conditions (starting blocks and tartan track equipped with force plates) during a quasi-standard training session.

The aims of this study were (a) to describe the sprint acceleration mechanics (i.e., spatiotemporal patterns, kinetics, F-V, P-V, and RF-V relationships) in elite and sub-elite sprinters in order to give a new mechanical insight into the limits of human sprint acceleration; and (b) to analyze the correlations between these parameters and sprint performance in order to further investigate the determinants of sprint acceleration performance.

We hypothesized that, as already reported on recent treadmill studies, the mechanical profile of elite and sub-elite sprinters maximally accelerating on a track can be characterized (a) by the F-V relationship using a linear model and (b) by the P-V relationship using a quadratic model. We also hypothesized that the higher acceleration of world-class sprinters compared with sub-elite athletes is related to a higher maximal power associated with a better (i.e., more forward) orientation of the force onto the ground.

Materials and methods

Participants

Nine elite or sub-elite sprinters (age: 23.9 ± 3.4 years; body mass: 76.4 ± 7.1 kg; height: 1.82 ± 0.69 m) gave written informed consent to participate in this study, conducted according to the declaration of Helsinki and in accordance with the local ethical committee. The elite group (E) was composed of four athletes who had been medalists in a sprint event during the (a) 2011 outdoor World championships (Daegu, South Korea) and/or (b) 2012 outdoor (Helsinki) and/or 2013 indoor (Göteborg, Sweden) European championships (including the 60-m champion) and/or finalists in the 2012 Summer Olympics (London). Their personal 100-m best times ranged from 9.95 to 10.29 s. The sub-elite group

(SE, $n = 5$) was composed of French national-level sprinters (100-m records range from 10.40 to 10.60 s).

Material and experimental protocol

Participants were tested at the indoor stadium of the French Institute of Sport (INSEP) during a quasi-standard sprint training session. After a 45-min warm-up managed by their personal coach, the athletes performed seven sprints: 2 × 10 m, 2 × 15 m, 20 m, 30 m, and 40 m with 5 min of rest between each trial. During these sprints, vertical, anteroposterior, and lateral components of the GRF were measured by a 6.60-m long force platform system (natural frequency ≥500 Hz). This system consisted of six individual force plates (1.2 × 0.6 m) connected in series and covered with a tartan mat that was level with the stadium track. The second force plate is turned by 90 degrees to allow the athletes' hands positioning during the start. Each force plate was equipped with piezoelectric sensors (KI 9067; Kistler, Winterthur, Switzerland). The force signals were digitized at a sampling rate of 1000 Hz.

Based on the original work of Cavagna et al. (1971), the protocol was designed in order to reconstruct the characteristics of a single virtual 40-m sprint for each athlete. This distance corresponds to the sprint acceleration. For example, it was shown in world-class athletes that the velocity measured between 30 and 40 m is greater than 95% of the maximal velocity reached during the 100-m sprint (Krzysztof & Mero, 2013). To this end, the starting blocks, initially placed over the first platform for the 10-m sprints, were progressively installed remotely for the subsequent trials (15 to 40 m) so that 18 foot contacts from the block to the 40-m mark could be evaluated. Indeed, the measurement area made it possible to record the force of five foot contacts (four steps) for the 10-m trials (including the pushing block phase), four contacts (three steps) for the 15-m trials, and three contacts (two steps) for the three other trials (20-, 30-, and 40-m). In addition, an optical measurement system (Optojump Next, Microgate, Bolzano, Italy) measured the spatiotemporal characteristics of the first steps of all seven sprints in order to assess the consistency of the first seven steps pattern (see Statistical analysis section).

Running velocity was measured with both the force platform system and a digital camera (Exilim EX-F1, Casio, Tokyo, Japan) that filmed the athletes in the sagittal plane as they entered the force platform area (see Data processing section).

Data processing

Sprint mechanics

For all measured variables, unless otherwise specified, the mechanical parameters described in the succeeding text represent the average of instantaneous data recorded during each contact. Regarding the parameters recorded twice (i.e., for the 10-m and 15-m runs), only the values of the trial corresponding to the best performance (best time over the distance) were selected. Moreover, for several mechanical variables, all the values measured during all the contacts over the 40 m were averaged (see Table 1, averaged F_Z, averaged F_Y, averaged P_Y and averaged RF).

Force platform signal was low-pass filtered (200 Hz cutoff, third order Butterworth applied forward and backward for zero phase shifting) and instantaneous data of vertical [F_Z, Fig. 1(a)] and horizontal [anteroposterior, F_Y, Fig. 2(b); mediolateral, F_X, Fig. 1(c)] components of ground reaction forces as well as the resultant GRF (F_{TOT}) were averaged for each contact phase (F_Z above 10 N) during the best 10-m and 15-m trials and during the 20-, 30-, and 40-m trials and expressed in N and body weight (BW). They are noted as F_{Zmean}, F_{Ymean}, F_{Xmean}, and $F_{TOTmean}$, respectively. The anteroposterior acceleration of the center of mass (COM) (A_Y) was calculated as follows

$$A_Y = F_Y / m$$

with m as the body mass.

This expression was integrated once over time to provide instantaneous anteroposterior velocity of the COM (V_Y) at time t:

$$V_Y = V_{0Y} + \int_t A_Y dt$$

with initial velocity conditions V_{0Y} taken as an integration constant.

Apart from the 10-m tests, for which $V_{0Y10} = 0$ m/s as the starting blocks were placed over the force platform area, V_{0Y15}, V_{0Y20}, V_{0Y30}, and V_{0Y40} were evaluated by high-speed video. A digital camera was placed in a fixed position perpendicularly to the sagittal plane. Focus and zoom were adapted in order to be able to follow an entire step cycle of the subject before the entrance in the force platform area. The motion in the sagittal plane of three retroreflective markers placed on the anterior superior iliac spine, posterior superior iliac spine, and the great trochanter was recorded at 300 Hz (resolution: 512 × 384). Anteroposterior position of the markers was determined by digitizing them with a video analyzing system (Dartfish, Fribourg, Switzerland). Then, after classically calibrating the camera view (3.80 m, ratio length/pixel: 0.0073 m/pixel), the horizontal distance covered by each marker was measured between two key positions: the beginning and the end of the last entire step cycle (i.e., contact + aerial phases) preceding the first foot contact on the force platform. The coordinates between the beginning and the end of this cycle, as they were measured in the same body position, were used to calculate a mean horizontal velocity of the subject. As V_{0Y} corresponds to the velocity during the aerial part of this phase, the mean velocity over the step was corrected taking into account the variation that occurred during the preceding contact on the basis of the measurement of instantaneous variation of the horizontal velocity in the subsequent two or three steps performed on the force plate.

V_{Ymean} was calculated for each recorded step and corresponds to the averaged anteroposterior velocity during the contact phase of the best 10- and 15-m trials and during the 20-, 30-, and 40-m trials. Instantaneous P_Y was obtained by the product of instantaneous F_Y and V_Y. The net power output in the anteroposterior direction (P_{Ymean} in W and W/kg) was calculated for each contact phase by averaging the instantaneous P_Y values during the contact. In order to quantify the contribution of the anteroposterior component of the GRF to the total force, a RF was calculated as the ratio of F_Y to F_{TOT} for each contact period (Morin et al., 2011; 2012). For this purpose, the ratio was done instantaneously and then averaged for each contact phase. Furthermore, to our best knowledge, RF parameter has only been assessed in two dimensions yet (i.e., vertical and horizontal anteroposterior axes). Then, in order to assess the part of the lateral force produced by the sprinters with respect to the resultant total force, we quantified the difference between RF variables expressed with respect to F_{TOT}, the sum of the force vectors measured on x, y, and z axes, and to F_{TOTyz}, the sum of the forces measured in the sagittal plan only (y and z axes).

Before pooling the data to reconstruct a complete 40-m dataset for each subject, running pattern repeatability was quantified on the sixth step (around 8-m distance), which was the last step common to all subjects before the end of the shorter sprint (10-m distance). High repeatability was observed for all variables – time performance at the end of the sixth step [mean = 1.309 s, coefficient of variation (CV) = 1.84%, intraclass correlation coefficient (ICC) = 0.921], total distance at the end of the sixth step (mean = 7.88 m, CV = 1.88%, ICC = 0.958), step length (mean = 1.60 m, CV = 2.15%, ICC = 0.946), contact time (mean = 0.136 s, CV = 3.76%, ICC = 0.686) – showing that all

Table 1. Mean values (SD) of the main sprint performance and spatiotemporal parameters, force-, power-, and RF-velocity relationships for the whole group ($n = 9$) and for both subgroups (elite, E: $n = 4$; sub-elite, SE: $n = 5$)

Variable	Mean all (SD) ($n = 9$)	Mean E (SD) ($n = 4$)	Mean SE (SD) ($n = 5$)	Difference (%E)	ES (Cohen's d)
Sprint performance					
10 m time (s)	1.85 (0.10)	1.79 (0.02)	1.90 (0.12)	−6.1	1.10
15 m time (s)	2.50 (0.10)	2.40 (0.02)	2.58 (0.09)	−7.5	1.80
20 m time (s)	3.05 (0.13)	2.94 (0.02)	3.13 (0.13)	−6.5	1.46
30 m time (s)	4.08 (0.18)	3.93 (0.03)	4.20 (0.15)	−6.9	1.50
40 m time (s)	5.10 (0.25)	4.90 (0.07)	5.27 (0.21)	−7.6	1.48
40 m maximal velocity (m/s)	9.78 (0.52)	10.24 (0.19)	9.33 (0.31)	8.9	3.64
Spatiotemporal parameters					
Contact time					
$t_{c\ blocks}$ (ms)	396 (33)	376 (13)	412 (36)	−9.6	1.09
Maximal contact time (ms)	193 (28)	191 (18)	193 (30)	−1.0	0.07
Minimal contact time (ms)	94 (4)	94 (5)	94 (4)	0.0	0.0
Aerial time					
$t_{a\ blocks}$ (ms)	75 (20)	81 (13)	70 (25)	13.6	0.55
Maximal aerial time (ms)	124 (7)	120 (6)	128 (5)	−6.7	1.14
Minimal aerial time (ms)	50 (13)	42 (13)	56 (10)	−33.3	1.04
Step frequency					
Sf_{blocks} (Hz)	2.14 (0.17)	2.20 (0.12)	2.09 (0.21)	5.0	0.64
Minimal frequency (Hz)	3.92 (0.34)	3.94 (0.44)	3.90 (0.44)	1.0	0.11
Maximal frequency (Hz)	4.87 (0.23)	4.95 (0.12)	4.80 (0.30)	3.0	0.65
Step length					
Sl_{blocks} (m)	0.99 (0.11)	0.96 (0.16)	1.01 (0.06)	−5.2	0.45
Minimal step length (m)	1.11 (0.12)	1.18 (0.07)	1.06 (0.14)	10.2	1.00
Maximal step length (m)	2.19 (0.11)	2.22 (0.10)	2.17 (0.12)	2.3	0.45
Force- and power-velocity parameters					
Averaged F_Z (N/kg)	17.3 (0.5)	17.2 (0.4)	17.5 (0.5)	−2.0	0.59
Averaged F_Y (N/kg)	3.3 (0.3)	3.5 (0.6)	3.1 (0.2)	9.7	1.75
Averaged P_Y (W/kg)	20.8 (2.2)	22.5 (1.1)	19.4 (1.9)	13.9	1.99
Averaged RF (% F_{TOT})	19.2 (1.3)	20.3 (0.7)	18.3 (1.0)	9.7	2.31
V0 (m/s)	11.38 (0.84)	11.90 (0.23)	10.99 (0.97)	7.6	0.12
F_Y0 (N)	776 (93)	855 (60)	744 (90)	13.0	1.19
Relative F_Y0 (N/kg)	9.77 (0.84)	9.95 (0.67)	9.62 (1.06)	3.3	0.39
Theoretical P_{Ymax} (W)	2328 (295)	2550 (283)	2150 (158)	15.7	1.35
Measured P_{Ypeak} (W)	2421 (321)	2695 (244)	2201 (158)	18.3	1.53
Relative P_{Ymax} (W/kg)	29.3 (2.3)	31.1 (0.8)	27.8 (2.2)	10.6	1.43
Relative P_{Ypeak} (W/kg)	30.5 (2.9)	32.9 (1.2)	28.5 (2.1)	13.4	1.51
RF0 (%)	70.6 (5.4)	71.6 (2.6)	70.1 (7.3)	2.1	0.02
D_{RF}	−0.067 (0.007)	−0.064 (0.003)	−0.069 (0.009)	−7.8	0.71
Mean difference RF_{xyz} – RF_{xy} (% RF_{xyz})	0.25 (0.06)	0.29 (0.03)	0.21 (0.03)	27.6	1.33
Measured block parameters					
Block clearing anteroposterior velocity (m/s)	3.37 (0.27)	3.61 (0.08)	3.17 (0.19)	12.1	1.60
$F_{Yblocks}$ (N)	679 (110)	783 (59)	596 (46.9)	23.9	1.70
Relative $F_{Yblocks}$ (N/kg)	8.56 (1.18)	9.59 (0.53)	7.74 (0.82)	19.2	1.56
$P_{Yblocks}$ (W)	1156 (270)	1415 (118)	949 (124)	32.9	1.72
Relative $P_{Yblocks}$ (W/kg)	14.5 (3.0)	17.3 (1.3)	12.3 (1.9)	28.8	1.64
RF_{blocks} (%)	58.9 (5.4)	63.0 (2.6)	54.9 (4.3)	12.8	1.46

Minimal and maximal parameters referred to the values recorded on the whole acceleration phase (0–40 m) excluding the block phase. ES, effect size; RF, ratio of force.

bouts were performed with the same maximal involvement regardless of the total distance (10- to 40-m). After computation, all data were then pooled from the seven sprints and used to draw overall F-V, P-V, and RF-V relationships.

Using linear and second-order polynomial regressions from these individual relationships, theoretical parameters were quantified: (a) F_Y0, maximal anteroposterior force theoretically produced over one contact phase at null velocity; (b) V0, maximal anteroposterior velocity reached when the anteroposterior force is equal to zero; and (c) P_{Ymax}, maximal anteroposterior power identified as the apex of the P-V relationship. Regarding RF-V relationships, RF0 represents the theoretical maximal contribution of anteroposterior force to the total force produced over one contact phase at null velocity. An index of force application technique (D_{RF}) was computed for each participant as the slope of the linear RF-V relationship. For details, see Morin et al. (2011, 2012), EJAP.

Given the bilateral nature of the start phase, F-, P-, and RF-V regressions were quantified excluding the values measured in the blocks. The maximal theoretical values must be differentiated from the maximal values measured from the 18 recorded contact phases and noted as F_{Ypeak}, V_{Ypeak}, and P_{Ypeak}. The start was specifically analyzed and the parameters measured in the block phase were noted as $F_{Yblocks}$, $P_{Yblocks}$, and RF_{blocks}.

The following step spatiotemporal variables were measured using the force platform system: contact time (t_c, in s), aerial time

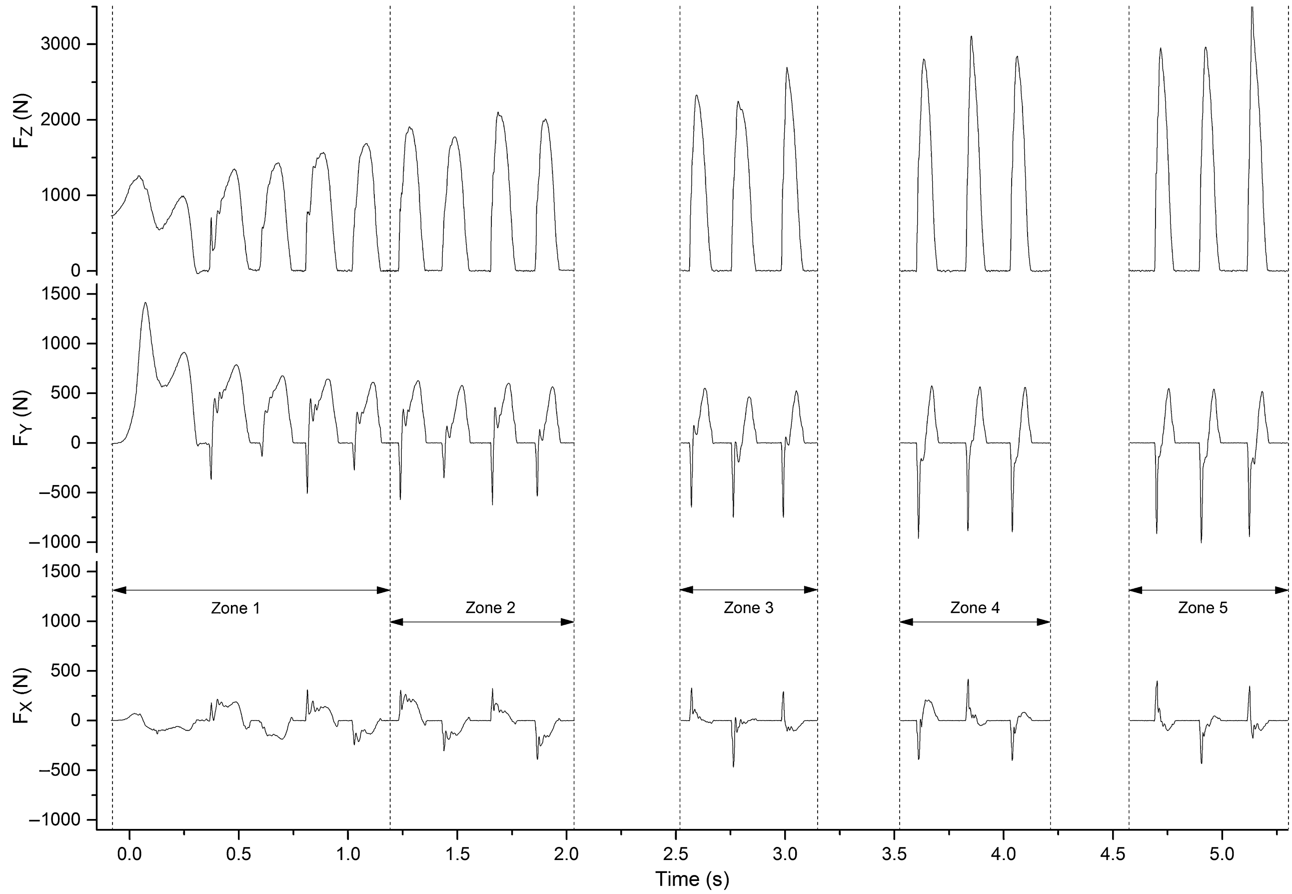

Fig. 1. Typical signals of instantaneous vertical (F_Z), anteroposterior (F_Y), and lateral (F_X) component of the ground reaction force (in N) obtained during the 10-, 15-, 20-, 30-, and 40-m trials that correspond to the following location of the force-plate area: (a) 10-m trials: Zone 1 (−1.4 to 5.2 m; 0 corresponding to the starting line); (b) 15-m trials: Zone 2 (4.6–11.2 m); (c) 20-m trial: Zone 3 (12.4–19.0 m); (d) 20-m trial: Zone 4 (22.4–29.0 m); (e) 20 m trial: Zone 5 (32.4–39.0 m).

(t_a, in s), step frequency (S*f*) and step length (S*l*). Regarding the block phase, the following spatiotemporal parameters were computed:

$t_{c\ blocks}$, contact time in the blocks, measured during the stabilization phase just before the start (where F_Z = body weight), represents the period from the time corresponding to a change higher than 10 N of F_Z to the block clearance (defined as the moment the forward foot takes off from the block and where $F_Z = 0$).

$t_{a\ blocks}$, aerial time from the blocks, period between the block clearance and the beginning of the following foot contact.

Sf_{blocks}, step frequency from the blocks, calculated as follow:

$$S_{f\ \mathrm{blocks}} = 1/\left(t_{c\ \mathrm{blocks}} + t_{a\ \mathrm{blocks}}\right)$$

Sl_{blocks}, step length from the forward block to the contralateral foot landing position.

Statistical analysis

Results were expressed as mean (± SD). To assess whether the running pattern was similar for each of the seven sprints, the repeatability of the sixth step (for details, see Data processing section) was quantified for time performance, total distance, step length, and contact time using the ICC and CV (Hopkins, 2000). In order to compare elite and sub-elite athletes, considering the small population inherent to the selection of high-level athletes, only the differences (expressed in percentage of elite group values) and the effect size (ES, Cohen's d) were calculated. For this effect size calculation, the results were interpreted as negligible, small, medium, or large for ES lower than 0.2, between 0.2 and 0.5, between 0.5 and 0.8, or higher than 0.8, respectively. When they were suitable ($P < 0.05$, least chi-square method), linear and quadratic regression models were used to fit the relationship between the different mechanical variables and the running velocity. Pearson's correlation coefficients were used to examine the relationships between spatiotemporal or mechanical variables and the performance. The critical level of significance was set at $P < 0.05$.

Results

Forty-meter performance and spatiotemporal parameters

Table 1 summarizes the mean values (SD) of the track performances recorded during each sprint trial (from 10- to 40-m). The 40-m was run in 5.10 ± 0.25 s, with a top speed of 9.78 ± 0.52 m/s. Table 1 also presents the values during or immediately after the first propulsion from the starting blocks together with the minimal and maximal values recorded during different sprints. The

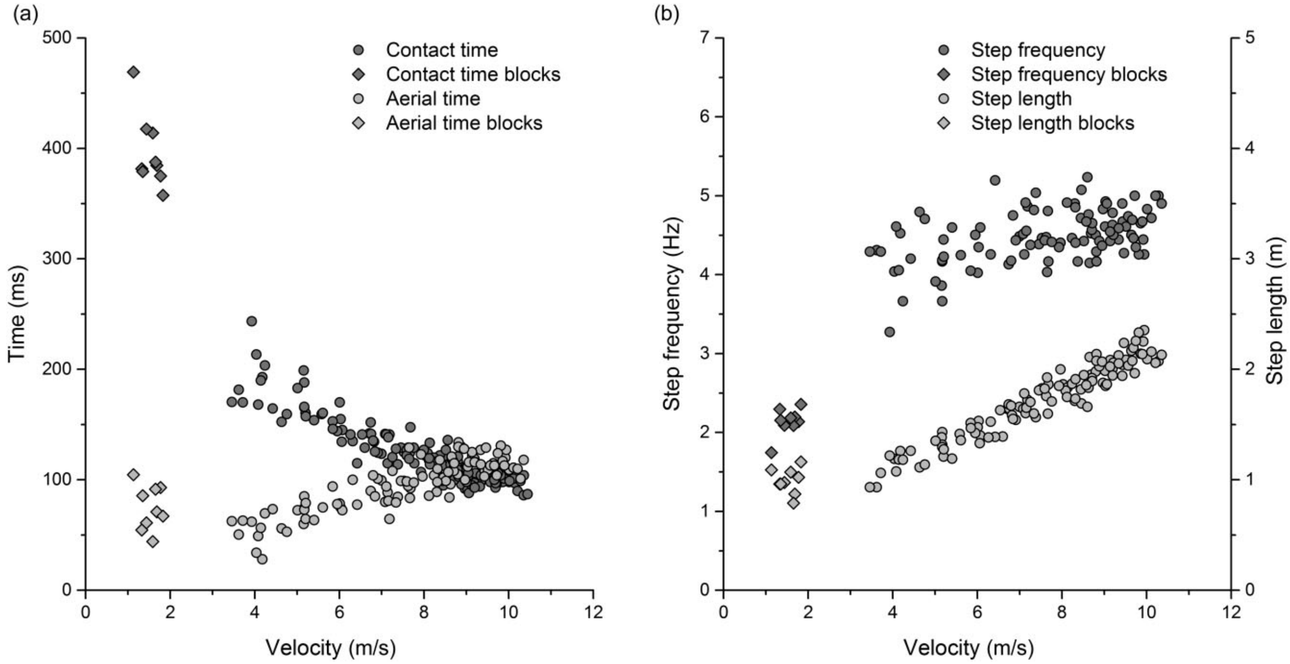

Fig. 2. Spatiotemporal characteristics of the step (a) during (contact time, in ms) or immediately after [aerial time (ms), step frequency (Hz), step length (m)] the first propulsion in the starting blocks and (b) during the acceleration phase (second to last steps) depicted against the forward velocity (m/s).

changes in the main spatiotemporal characteristics of the step when velocity increases are presented in Fig. 2 for all subjects. The contact time decreased on average by about 50% between the first (blocks) and second steps and the same relative decrease occurred between the second step and the 40-m minimal contact time (last step) (Table 1). Mean values of aerial time just after the start (between the blocks clearing and the contact of the second step) were about five times lower than the propulsion time in the starting blocks. This aerial time decreased by around one-third on average after the second step and increased linearly with the velocity to reach the same values as contact time. While step frequency was smaller by half at the first step compared with the second step, step length did not change. Between the second and last steps, step frequency and step length increased by about 20% and 50%, respectively.

F-V, P-V, and RF-V relationships

The parameters F_{Ymean} and P_{Ymean} as a function of the horizontal velocity were well described by significant linear (mean $R^2 = 0.892 \pm 0.049$) and quadratic relationships (mean $R^2 = 0.732 \pm 0.114$), respectively (Fig. 3). The parameter F_{TOT} showed an increase in velocity that was best described by a linear model (mean $R^2 = 0.815 \pm 0.023$). Regarding the orientation of force onto the ground, the RF decreased with velocity and this relationship was linear for all subjects (mean $R^2 = 0.950 \pm 0.023$). Table 1 also presents the theoretical maximal values calculated from these relationships (F_Y0, V0, Py_{max}, RF0) and the slope of the RF-V relationship (D_{RF} index). On average, the athletes reached P_{Ymax} at around the sixth step (6.22 ± 1.2 steps).

In order to assess the part of the lateral force produced by the sprinters, we quantified the difference between RF variables expressed with respect to (a) F_{TOT}, the resultant force measured on x, y, and z axes, and (b) F_{TOTyz}, the resultant force measured in the sagittal plan only (y and z axes). The mean difference, expressed in percentage of F_{TOT} was 0.25 ($\pm$ 0.03) %.

Correlations between mechanical and performance variables

The correlation analyses of spatiotemporal parameters, force, and power are presented in Table 2.

Discussion

The aims of this study were, first, to characterize the sprint acceleration mechanics (i.e., spatiotemporal patterns, kinetics, F-V, P-V, and RF-V relationships) in elite and sub-elite sprinters and, second, to analyze the correlations between these parameters and sprint performance in order to further investigate the determinants of sprint acceleration performance. The reconstruction of a virtual 40-m sprint allowed us to describe for the first time the mechanical characteristics of the acceleration phase in

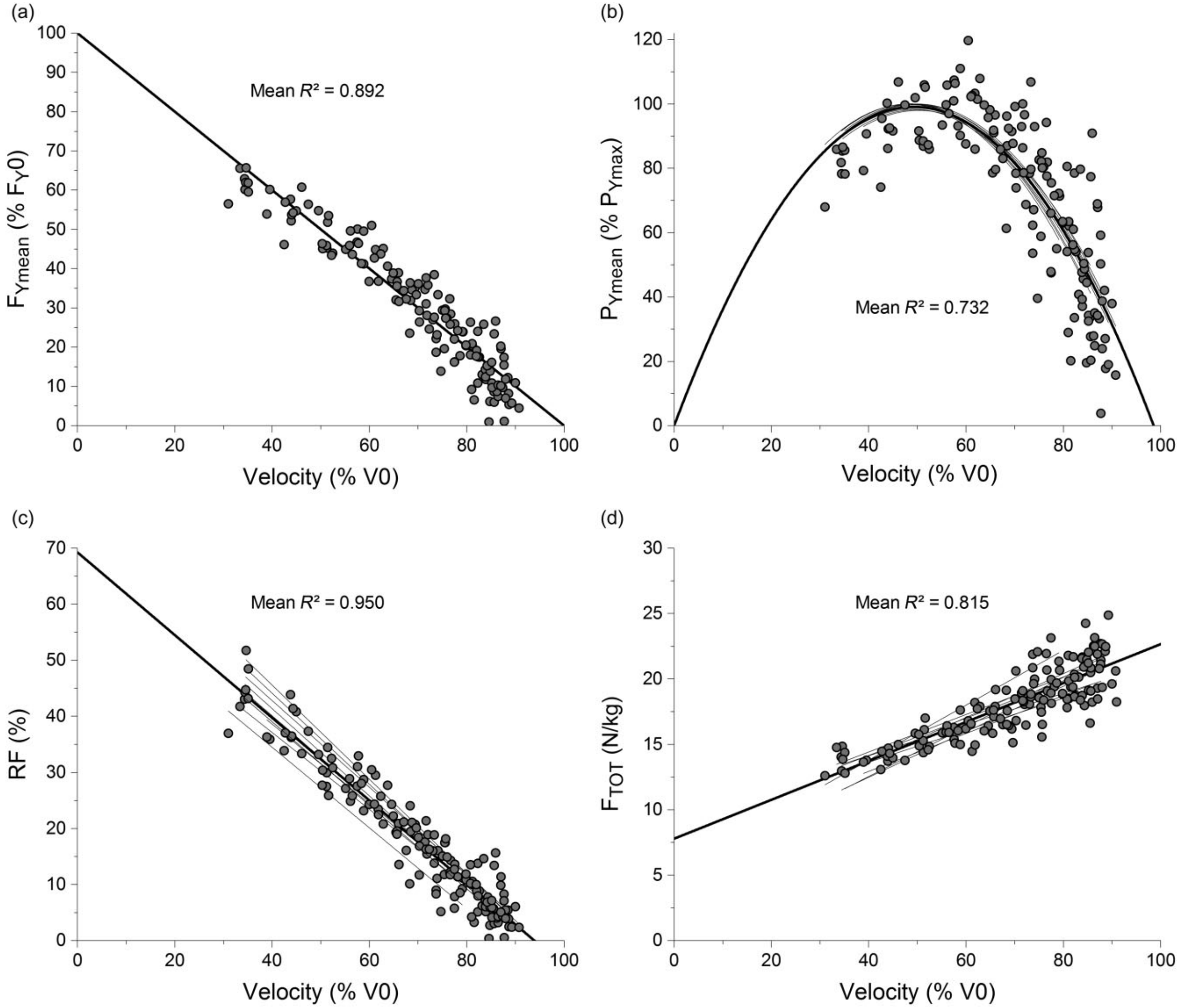

Fig. 3. (a) Anteroposterior component of the ground reaction force (F_{Ymean}, in % theoretical anteroposterior maximal force, F_Y0); (b) anteroposterior power output (P_{Ymean}, in percentage of theoretical maximal power, P_{Ymax}); (c) ratio of force (RF, in % of the total force) and (d) total force (in N/kg) in relation to the anteroposterior velocity (in % V0, theoretical maximal velocity). For each relationship, the mean R^2 are presented on graphs. Thin (individual models) and thick lines (mean trend curves) are shown for information and clarity purposes.

world-class and sub-elite sprinters. The main findings of this study show that (a) while step length increases regularly during the acceleration phase, step frequency is almost instantaneously leveled at the maximal possibility of elite athletes; (b) F- and P-V relationships during sprints performed in realistic field conditions were well described by linear and quadratic models, respectively; and (c) the effectiveness of force application greatly accounts for the difference in the performance between highly trained athletes.

Spatiotemporal parameters have shown that the step frequency very quickly reached the maximal values (80% at the first step and about 90% after the third step) and then remained constant throughout the acceleration phase (Fig. 2). These results are consistent with the recent study by Debaere et al. (2013b) who reported that high-level sprinters are capable of developing in the starting phase (0–10 m) a step frequency higher than 95% of the step frequency reached at maximal speed during a 60-m sprint. The acceleration of high-level athletes is afterwards quasi-exclusively related with the increase in step length (Debaere et al., 2013b). The mechanical mechanisms leading to such spatiotemporal patterns are partly described by kinetics data.

The individual F-V relationships are aptly described by linear models (Fig. 3; mean $R^2 = 0.89$). These results were expected from previous treadmill findings (Jaskolska et al., 1999; Morin et al., 2011, 2012) despite the fact that some of the sprint mechanics variables

Table 2. Pearson's correlation coefficient between performance and spatiotemporal or mechanical variables

	Block clearing speed (m/s)	Measured 40-m maximal speed (m/s)	40-m performance (m/s)
Spatiotemporal parameters			
Mean step frequency	0.120	0.424	0.236
Maximal step frequency	0.070	0.236	0.176
Mean step length	0.631	0.518	0.544
Maximal step length	0.394	0.467	0.444
Force components			
Averaged F_Z (N/kg)	−0.241	−0.216	−0.388
Averaged F_Y (N/kg)	0.775*	0.904***	0.816**
Averaged F_{TOT} (N/kg)	−0.021	−0.137	−0.228
Force- and power-velocity relationship variables			
Theoretical F_Y0 (N/kg)	−0.129	0.108	0.079
Theoretical V0 (m/s)	0.878***	0.819**	0.803**
Theoretical P_{Ymax} (W/kg)	0.868**	0.932***	0.932***
Averaged P_Y (W/kg)	0.919***	0.958***	0.903***
RF-velocity relationship variables			
RF0	0.135	0.071	0.149
Averaged RF	0.821**	0.899***	0.933***
D_{RF}	0.634	0.470	0.408
Block parameters			
$F_{Y\ blocks}$ (N/kg)	0.873**	0.836**	0.850**
$P_{Y\ blocks}$ (W/kg)	0.964***	0.909***	0.902***
RF_{blocks} (%)	0.858***	0.741**	0.829***

*, **, and *** denote a significant correlation at $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively. RF, ratio of force.

differ between treadmill and overground running (McKenna & Riches, 2007). Regarding the individual P-V relationships, the quadratic models present lower coefficients of determination (Fig. 3; mean $R^2 = 0.73$). This could be explained by (a) the very few number of steps in the ascending part of the relationship inherent in the high acceleration capability of the sprinters who produce their maximal power after about six steps; (b) possible asymmetry between right and left legs considering that the actions of both lower limbs were taken into account in the models; and (c) interstep variability because of the great muscle coordination complexity of the sprint start phase. Nevertheless, the quadratic model is still acceptable (mean $R^2 = 0.73$), as shown by the strong correlation between the predicted theoretical maximal power (P_{max}) and the maximal measured power (P_{peak}) (R = 0.91; $P < 0.001$). To our knowledge, the present study is the first to describe these biomechanical relationships in elite athletes from sprint exercises performed in the field and almost similar to competition conditions. This novelty offers new insight into sprint mechanics in humans as it allows for the first time linking the horizontal force or power output to the associated realistic velocity. The fact that the population was partially composed of world-class athletes, including the 2013 60-m indoor European Champion, strongly suggests that the modeled F-V and P-V relationships mechanically characterize the current human limits of the sprint acceleration. From a practical viewpoint, the use of these relationships should be very useful for training as it allows the specific and individual determination of a range of power by means of a simple variable: the velocity expressed relatively to the theoretical maximal speed, i.e., independently of the athlete's performance. In this context, the use of current motorized pulling devices (e.g., Kawamori et al., 2014) adequately leveled should be very useful in order to specifically calibrate the training sessions.

Regarding the correlations between sprint performance and the measured mechanical variables, the analyses strengthen the previous findings of Morin et al. (2011, 2012). Firstly, performance parameters of the acceleration phase were highly related to theoretical maximal and averaged velocity and power measured in the forward direction and obtained from F-V and P-V relationships. Secondly, theoretical maximal anteroposterior ground reaction force (F_Y0) was not significantly correlated with these performance parameters, whereas the averaged anteroposterior force was. These results suggest that the ability of the athletes to generate high net anteroposterior (horizontal) GRF, especially at high velocity, seems more essential to improve sprint acceleration and thus overall performance than their capability to produce very high levels of resultant GRF. The latter represents the total resulting force output from all lower limbs muscle actions (i.e., how much total force is produced), whereas the former represents the horizontally oriented component of this resultant GRF (i.e., what part of this total force production is oriented in the forward direction). Thirdly, neither the resultant GRF, nor its vertical component was significantly related to any of the sprint acceleration performance parameters. The present findings, in conjunction with previous studies (Kyröläinen et al., 2001; Nummela et al., 2007;

Brughelli et al., 2011), both confirm the mechanical logic that horizontal net GRF is paramount to accelerate the body forward. It seems important to notice that the vertical GRF has a major influence on the sprint mechanics as the athletes have to produce the vertical force needed to overcome the negative vertical acceleration because of gravity. However, our results support the argument that the vertical component of the GRF is not by itself a determinant of performance in high-level athletes during the sprint acceleration phase. These results also clearly confirm that the biomechanical determinants of the sprint acceleration phase differ from those related to the final top-speed phase. Indeed, the study by Weyand et al. (2000), who analyzed a heterogeneous population of subjects (overground maximal 100-m speed ranged from 6.2 to 11.1 m/s) during a treadmill top-speed test, concluded that human runners reached faster top speeds by applying greater support forces to the ground. More recently, using a subtle one-legged and backward moving protocol, the same research group (2010) brought the specification that the mechanical limit for top speed was in the maximal vertical GRF possibly produced within the stance phase duration, not in the absolute maximal level of vertical GRF subjects could produce, should movement conditions allow it. This importance of vertical GRF production in top-speed performance is in line with some results of Morin et al. (2011, 2012) who also found during treadmill tests in a population with different sprint levels – including moderate-level physical education students together with national-level sprinters and one world-class sprinter (maximal speed ranging from 7.8 to 11.2 m/s) – that the only sprint performance parameter significantly related to the vertical GRF production was the field 100-m top speed.

As mentioned earlier, in optimal motivation and physical shape conditions, the capability of an athlete to generate maximal power during a sprint acceleration mainly depends on (a) his neuromuscular characteristics and musculoskeletal mechanical properties and (b) his sprint technical ability to move his body mass forward. This technical ability could be reflected overall by the way an athlete orients horizontally the ground reaction force vector (e.g., Hunter et al., 2005; Morin et al., 2011, 2012). Firstly, our results revealed the negligible part of mediolateral forces confirming, for the entire acceleration phase, similar findings related to the starting phase in well-trained athletes (Debaere et al., 2013a). Secondly, the fact that averaged RF is one of the mechanical variables most highly correlated with the 40-m performance ($R^2 = 0.93$; $P < 0.001$) strengthens the hypothesis that the orientation of the total force that high-level sprinters applied to the ground during sprint acceleration is more important to performance than its magnitude (Morin et al., 2011, 2012). These findings were well summarized in Fig. 4, which differentiates elite from sub-elite athletes: (a) F-V relationships clearly show that elite sprinters are able to produce higher horizontal force at any given velocity than sub-elite sprinters; (b) the RF-V relationships show that this higher horizontal force production was caused by a better (i.e., more forward) orientation of the force onto the ground given that (c) the sub-elite sprinters did not show lower resultant force production but on the contrary, a tendency to produce higher F_{TOT} than elite, especially at high velocities. The fact that elite athletes are able to orient their GRF vector more effectively than sub-elite athletes explained part of the difference between these two groups in terms of anteroposterior power production (Fig. 4). Moreover, this increased effectiveness in elite sprinters is due to specific neuromuscular properties (coordination, muscle-tendon mechanical properties, joint moment-angle relationships, etc.) that lead *in fine* to their better technical ability of force application. Indeed, more powerful specific muscle groups (e.g., hip extensors) and muscle groups involved in the foot–ground interaction (e.g., ankle joint stabilizers) could also be involved in an appropriate coordination and high joint moments that finally result in a better orientation of the resultant force produced. Further research focusing on the determinants of a high RF is therefore requested.

The D_{RF} variable reflects the ability of runners to produce and maintain high levels of RF over the entire acceleration despite the overall straightening up of their body with increasing speed (Morin et al., 2011, 2012). As such, this index of force application technique is closely linked to the sprinter's training background. These authors demonstrated that this parameter was highly related to performance in a heterogeneous population; however, this was not the case in the present study, which could be explained by the fact that the present population was exclusively composed of highly trained athletes. Briefly, the fact that the mean RF parameter was significantly related to performance and not the D_{RF} variable simply reflects that the slowest well-trained sprinters, who orient their ground reaction forces less effectively than the speediest athletes, do not, however, deteriorate this ability more than them with increasing speed.

Finally, our results show that all the variables significantly related to the mean and maximal 40-m speed were also highly related with the block clearing speed (Table 2). These results are in agreement with previous studies that showed the essential contribution of the starting phase in the sprint performance (Harland & Steele, 1997; Slawinski et al., 2010; Debaere et al., 2013a). However, despite the very good linear adjustment of the F- and RF-V relationships, theoretical values extrapolated to zero velocity axis (F_Y0 and RF0) showed no significant correlation with sprint performance. In contrast, both the anteroposterior force and the ratio of force measured or computed from the starting block phase did. These results suggest that (a) $F_{Yblocks}$ and

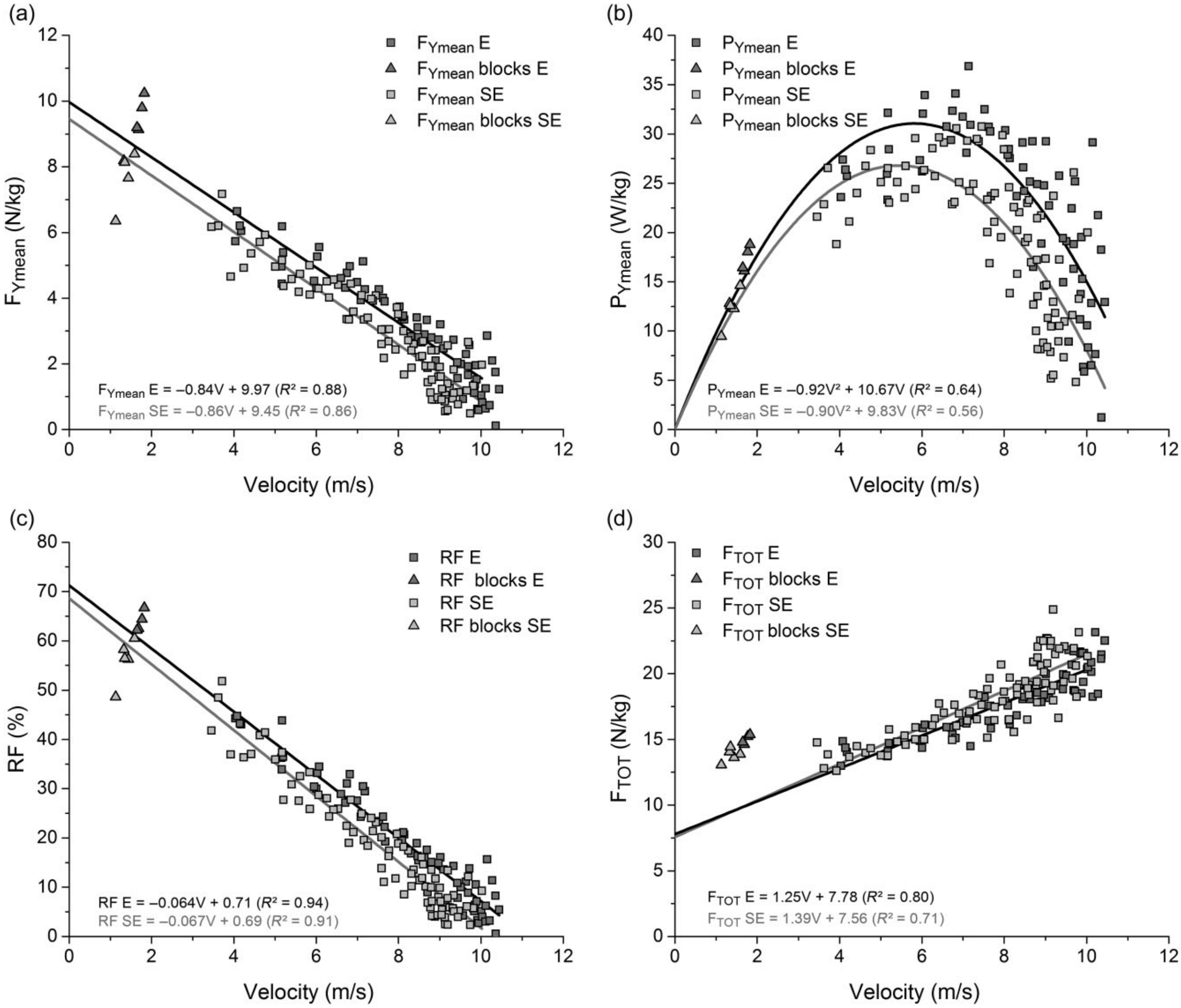

Fig. 4. (a) Anteroposterior component of the ground reaction force (F_{Ymean}, in N/kg; (b) anteroposterior power output (P_{Ymean}, in W/kg); (c) ratio of force (RF, in %) and (d) total force (in N/kg) were presented against the anteroposterior velocity (in m/s) for the elite (E; dark gray) and sub-elite (SE; light gray) groups. For each group, the linear or polynomial adjustments were computed excluding the block values (presented for information).

RF_{blocks} represent specific muscular and technical abilities that give complementary information with respect to F- and RF-V relationships (adjusted without taking into account the block phase) and that (b) the start specificity cannot be characterized either by the extrapolated data of F-V or those of RF-V relationships.

An obvious limitation of the present study is that mechanical data for virtual 40-m sprint acceleration were reconstructed from several sprints. Beyond the fact that no force-plate system allowing such long-distance measurements currently exists to the authors' knowledge, the high reproducibility shown between sprints (see Materials and methods section) supports the realistic feature of our virtual reconstruction approach.

Perspectives

The methods used here might not be easily reproduced by coaches in their typical training practice. This could limit the use of F-V and P-V relationships as done here, when seeking to analyze and improve sprint mechanics on an individual basis. One of the practical perspectives of this work is to validate a simple methodology to quantify these variables. Indeed, very recently, Samozino et al. (2013) proposed a simple field method to compute force, velocity, and power in field conditions from only split times or running velocity measurements by radar (e.g., Mendiguchia et al., 2014).

The findings of the present study allowed us to characterize the mechanics of the sprint acceleration phase in world-class and sub-elite sprinters. As such, they yielded new insights into some aspects of biomechanical limits in human locomotion, notably by modeling the relationships between the realistic velocity reached by athletes on overground conditions and three key variables of the sprint: the anteroposterior force, the ratio of force, and the anteroposterior power output. The opportunity to tests such sprinters allowed further insights into the mechanical determinants of high-level sprint performance. Beyond the expected ability to produce high-power output or forward force component, the effectiveness of force application during the acceleration phase, represented by the averaged ratio of force, is one of the abilities most closely linked to performance. This was not the case for the total amount of force that a sprinter can produce. Furthermore, the muscular and technical athletes' capability during the starting phase, represented by anteroposterior force and the ratio of force recorded in the blocks, is essential for performance and would complement the F-, P-, and RF-V models to characterize the mechanics of the sprint acceleration. From a practical viewpoint, the results of the present study should be useful for coaches to determine the strengths and weaknesses of their elite sprinters.

Key words: Force orientation, performance, power output, running, elite sprinters.

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