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ORIGINAL ARTICLE

Mechanical determinants of 100-m sprint running performance

Jean-Benoît Morin · Muriel Bourdin ·
Pascal Edouard · Nicolas Peyrot · Pierre Samozino ·
Jean-René Lacour

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Abstract Sprint mechanics and field 100-m performances were tested in 13 subjects including 9 non-specialists, 3 French national-level sprinters and a world-class sprinter, to further study the mechanical factors associated with sprint performance. 6-s sprints performed on an instrumented treadmill allowed continuous recording of step kinematics, ground reaction forces (GRF), and belt velocity and computation of mechanical power output and linear force–velocity relationships. An index of the force application technique was computed as the slope of the linear relationship between the decrease in the ratio of horizontal-to-resultant GRF and the increase in velocity. Mechanical power output was positively correlated to mean 100-m speed ($P < 0.01$), as was the theoretical maximal velocity production capability ($P < 0.011$), whereas the theoretical maximal force production capability was not. The ability to apply the resultant force backward during acceleration was positively correlated to 100-m performance ($r_s > 0.683$; $P < 0.018$), but the magnitude of resultant force was not ($P = 0.16$). Step frequency, contact and swing time were significantly correlated to acceleration and 100-m performance (positively for the former, negatively for the two latter, all $P < 0.05$), whereas aerial time and step length were not (all $P > 0.21$). Last, anthropometric data of body mass index and lower-limb-to-height ratio showed no significant correlation with 100-m performance. We concluded that the main mechanical determinants of 100-m performance were (1) a "velocity-oriented" force–velocity profile, likely explained by (2) a higher ability to apply the resultant GRF vector with a forward orientation over the acceleration, and (3) a higher step frequency resulting from a shorter contact time.

Keywords Performance · Force–velocity · Power output · Ground reaction force application

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J.-B. Morin · P. Edouard
University of Lyon, 42023 Saint Etienne, France

J.-B. Morin · P. Edouard
Laboratory of Exercise Physiology (EA4338),
42000 Saint-Etienne, France

J.-B. Morin (✉)
Laboratoire de Physiologie de l'Exercice (EA4338),
Médecine du Sport-Myologie, CHU Bellevue,
42055 Saint-Etienne cedex 2, France
e-mail: jean.benoit.morin@univ-st-etienne.fr

M. Bourdin · J.-R. Lacour
University of Lyon, University Lyon 1, IFSTTAR,
UMR_T9406, LBMC, 69921 Oullins, France

N. Peyrot
University of La Réunion, DIMPS (EA4075),
97430 Le Tampon, France

P. Samozino
Laboratory of Exercise Physiology (EA4338),
University of Savoie, 73376 Le Bourget-du-Lac, France

Introduction

The 100-m event is the standard measure of the extreme speed capabilities of human bipedal locomotion and defines the "world's fastest human" for a given time period. The scientific research about the limits of human locomotion and the determinants of sprint performance has, therefore, considered record holders and world champions as examples of the limits of muscular, physiological and mechanical features of human locomotion. Paradoxically,

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elite 100-m sprinters have been the specific focus of very few experimental studies. To our knowledge, only Weyand et al. (2000) presented experimental data obtained in the three 100-m medalists of the 1996 Olympic Games in a specific study about top speed production, and a more detailed physiological and biomechanical case study about the fastest sprinter with leg amputation (Weyand et al. 2009).

Further, data of sprint kinematics obtained during official events such as the World Championships in Athletics, i.e. not during specific experimental studies, have been published (e.g. Moravec et al. 1988). Other studies have considered world-class sprinters, but only used their official performance data as inputs of mathematical models (e.g. Arsac and Locatelli 2002; Beneke and Taylor 2010; Ward-Smith and Radford 2000), and did not perform or report specific experimental measurements. This lack of experimental data in elite sprinters contrasts with other competitive sports for which experimental case studies of world top-level athletes and world record holders have been published, for instance in rowing (Lacour et al. 2009), cycling (Coyle 2005), or middle-distance and marathon running (Jones 2006; Lucia et al. 2008). This may also be a limit to a thorough and clear understanding of the determinants of sprint running ability, specifically when the populations of sprint studies do not include top-level sprinters. In the present study, we had the unique opportunity to specifically study a group of subjects including a young world-class male sprinter, and three French national-level sprinters.

When considering the physiological correlates of 100-m performance, except for muscle fibers distribution (e.g. Baguet et al. 2011; Gollnick and Matoba 1984) and the capacity for using high-energy phosphates (Hirvonen et al. 1987), no clear consensus has been made from experimental data on the fact that 100-m performance and human maximal running speed were predominantly determined by physiological factors/pathways such as for instance lactate accumulation or clearance (e.g. Bret et al. 2003; Hirvonen et al. 1987). Consequently, and in light of existing studies about high-speed running mechanics, we propose that neurological and mechanical factors are more relevant to 100-m sprint performance and top speed in humans. For instance, Weyand et al. (2000, 2010) related the specific ability to run at high speed to the production of high amounts of vertical ground reaction force (GRF) per unit body weight (BW) (Weyand et al. 2000), and to the time needed/available to apply these high amounts of force onto the supporting ground (Weyand et al. 2010) through experimentally controlled research designs. Other scientists showed the important role of horizontal GRF and impulses in animals (e.g. Roberts and Scales 2002) and human (Hunter et al. 2005) acceleration capability.

The ability of athletes to specifically apply high amounts of GRF in the horizontal direction at the various speeds produced over a typical sprint acceleration is well described by linear force–velocity (F–V) relationships and 2nd degree polynomial power–velocity relationships (Jaskolska et al. 1999; Morin et al. 2010), as it is also the case in horizontal or incline push-off (e.g. Samozino et al. 2012) or cycling (e.g. Dorel et al. 2010). In particular, since mechanical power is the product of force and velocity, the slope of the linear F–V relationship (Jaskolska et al. 1999; Morin et al. 2010) may indicate the relative importance of force and velocity qualities in determining the maximal power output, and the individual F–V profile of each subject. Such individual F–V profiles have recently been studied and related to power output and performance in jumping exercises (Samozino et al. 2012). These individual F–V relationships describe the changes in external horizontal force generation with increasing running velocity and may be summarized through their two theoretical extrema: the theoretical maximal horizontal force the legs could produce over one contact phase at null velocity (F_H0), and the theoretical maximal velocity of the treadmill belt the legs could produce during the same phase under zero load ($V0$). These integrative parameters characterize the mechanical limits of the entire neuromuscular system during sprint running, encompass numerous individual muscle mechanical properties, morphological, neural and technical factors (Cormie et al. 2011) and, therefore, provide an integrative view of the F–V mechanical profile of an athlete in his specific sprint running task. In particular, although power output (yet quantified during other movements than sprint running: vertical jump, sprint cycling) was expected as highly correlated to sprint running performance (e.g. Cronin and Hansen 2005; Cronin and Sleivert 2005; Harris et al. 2008; Sleivert and Taingahue 2004), the relative importance of its force and velocity components was unknown.

Recently, continuous GRF measurements in three dimensions during a sprint acceleration were made possible with the use of an instrumented sprint treadmill (Morin et al. 2010). When comparing data of horizontal, vertical and resultant GRF, these authors showed that during the acceleration phase, the orientation of the resultant GRF vector, related to athletes' technical abilities, was a stronger determinant of field sprint performance than the magnitudes of vertical or resultant force vectors. Indeed, Morin et al. (2011a) showed that the magnitude of the horizontal component of the GRF per unit BW measured on the treadmill over an accelerated run was highly correlated to 100-m performance (mean and top running speeds), whereas the magnitude of the resultant GRF was not. They also defined an index of force application technique (D_{RF}), which quantifies a runner's ability to maintain a forward orientation of the resultant GRF vector despite increasing speed over the entire acceleration phase (see "Methods"). In two recent studies, the authors proposed and experimentally supported the idea that the D_{RF} index was significantly related to field 100-m performance (Morin et al. 2011a) and significantly altered with fatigue over a repeated sprint series (Morin et al. 2011b). They concluded that the orientation of the resultant force vector applied against the supporting ground during sprint acceleration was more important to 100-m performance than its magnitude. However, their conclusions were limited because these results were obtained in subjects of rather low level of sprint performance (ranging from non-specialists to regional-level sprinters).

Last, in parallel with these functional abilities of force production, some aspects of human body design have been suggested to be requirements for high sprinting speed: specifically a high BMI (Watts et al. 2011; Weyand and Davis 2005) and long limbs (van Ingen Schenau et al. 1994). The present study also allowed us to further discuss these anthropometric results.

The aim of this study was to investigate the detailed mechanical variables associated with field 100-m performance and discuss recent hypotheses about the mechanical determinants of sprint performance (Morin et al. 2011a; Weyand et al. 2000). To better elucidate the mechanical correlates of 100-m sprint performance, we used instrumented sprint treadmill measurements, performed in a group of subjects including a world-class and three national-level sprinters. This was thought useful to potentially moderate or strengthen the aforementioned results, especially the recent conclusions of Morin et al. (2011a) stating that the orientation of the resultant GRF vector onto the ground was more important to 100-m performance than its magnitude.

Methods

Subjects

Thirteen male subjects participated in the study. They had different sprint performance levels: nine of them were physical education students [age (mean ± SD) 26.5 ± 1.8 years; body mass 72.6 ± 8.4 kg; height 1.75 ± 0.08 m] who were all physically active and had all practiced physical activities including sprints (e.g. soccer, basketball) in the 6 months preceding the study, but were not sprint specialists. Three were French national-level sprinters [age (mean ± SD) 26.3 ± 2.1 years; body mass 77.5 ± 4.5 kg; height 1.83 ± 0.05 m]. Their personal best times on 100-m relay (last update September 5, 2011) ranged from 10.31 to 10.61 s. And one subject was a world-class sprinter (age 21 years; body mass 81.0 kg; height 1.91 m). His official best performances were (last update September 5, 2011): 9.92 s on the 100-m and 19.80 s on the 200-m. Among his official titles, he is French National Champion and record holder on 100- and 200-m, he has won the World Junior Championships on 200-m in 2008, and has been European Champion in 2010 on 100-, 200- and 4 × 100-m relay. More recently, he finished at the 4th and 3rd place on 100- and 200-m, respectively, at the 2011 World Championships in athletics. All subjects gave their written informed consent to participate in this study after being informed about the procedures approved by the local ethical committee and in agreement with the Declaration of Helsinki.

Experimental protocol

For each subject, two sets of measurements were performed: (1) a laboratory test consisting in performing a 6-s maximal sprint after full familiarization with the sprint treadmill and an appropriate standardized warm up, and (2) a field 100-m test performed on a standard synthetic track, after an appropriate standardized warm up. The non-specialist subjects performed these treadmill and field tests within a unique testing session, with treadmill and field sprints performed in a randomized counterbalanced order among subjects, and with about 30–45 min of passive rest between tests (for full details, see Morin et al. 2011a). The world-class and national-level sprinters were tested on two distinct occasions: in mid-March and mid-April 2011 (treadmill and field performance measurements, respectively). This corresponded to the training period just preceding the beginning of their official outdoor competitive season.

Instrumented treadmill

The motorized instrumented treadmill (ADAL3D-WR, Medical Development—HEF Tecmachine, Andrézieux-Bouthéon, France) used has recently been validated for sprint use (for details, see Morin et al. 2010). It is mounted on a highly rigid metal frame fixed to the ground through four piezoelectric force transducers (KI 9077b, Kistler, Winterthur, Switzerland), and installed on a specially engineered concrete slab to ensure maximal rigidity of the supporting ground. The constant motor torque was set to 160 % of the default torque, i.e. the motor torque necessary to overcome the friction on the belt due to subject's body weight. The default torque was measured by requiring subjects to stand still and then increasing the driving torque until observing a movement of the belt greater than 2 cm over 5 s. This default torque setting as a function of belt friction is in line with previous motorized-treadmill studies (e.g. Chelly and Denis 2001; Jaskolska et al. 1999; Morin et al. 2011a, b). Motor torque of 160 % of the default value was selected after several preliminary measurements comparing various torques. 160 % allowed subjects to sprint in a comfortable manner and produce maximal effort without risking loss of balance. Subjects were tethered by means of a leather weightlifting belt and a thin stiff rope (0.6 cm in diameter) rigidly anchored to the wall behind the subjects by a 0.4-m vertical metal rail. When correctly attached, subjects were able to lean forward in a typical crouched sprint-start position with their preferred foot forward. This starting position was standardized for all trials. After a 3-s countdown, the treadmill was started and the treadmill belt began to accelerate as subjects applied a positive horizontal force.

Sprint mechanics

Mechanical data were sampled at 1,000 Hz continuously over the sprints, the beginning of the sprint being determined with a velocity threshold of 0.2 m s^{-1}. After appropriate filtering (Butterworth-type 30 Hz low-pass filter), instantaneous data of vertical, horizontal and resultant GRF were averaged for each support phase (vertical force above 30 N) over the 6-s sprints (F_V, F_H and F_{Tot}, respectively), and expressed in N and BW. For each 6-s sprint, performance was described through mean and maximal running speeds (V and V-max, respectively). These data were completed by measurements of the main step kinematic variables: contact time (t_c in s), aerial time (t_a in s), step frequency (SF in Hz), step length (SL in m) and swing time (t_{swing}), i.e. the time to reposition the limb, from take-off to touch-down of the same foot.

For each step, the net power output in the horizontal direction was computed according to Morin et al. (2010) as $P = F_H V$, and expressed in W kg^{-1}. As for velocity, mean and maximal mechanical power outputs were calculated over the 6-s sprints (P and P-max, respectively). For each sprint, the linear F–V relationship was plotted from F_H (expressed in N kg^{-1}) and V values of steps ranging from the step at maximal F_H (typically one of the three first steps) to the step at V_{max}, as for Morin et al. 2010). These individual relationships were summarized through the theoretical maximal horizontal force that the legs could produce over one contact phase at null velocity (F_H0 in N kg^{-1}), and the theoretical maximal velocity of the treadmill belt that the legs could produce during the same phase under zero load ($V0$ in m s^{-1}).

To quantify this F_H production compared to the F_{Tot} production, a ratio of forces (RF in %) was calculated as the ratio of F_H to F_{Tot} for one contact period (Morin et al. 2011a). This ratio basically represents, for a given support phase, the percent of the resultant GRF that is applied in the forward direction. As recently presented by Morin et al. (2011a), an index of force application/orientation technique (D_{RF}) representing the decrement in RF with increasing running velocity was computed for each subject as the slope of the linear RF–velocity relationship calculated from step-averaged values between the second step and the step at top speed. A high value of D_{RF} (i.e. a flat RF–velocity relationship), indicates that the systematic linear decrease in RF with increasing velocity is rather limited, and vice versa (see for instance the typical comparison of two individuals in Fig. 2b of Morin et al. 2011a).

Field 100-m performance

The four athletes used spiked shoes and starting blocks during the field tests, which was not the case of the non-specialists. The latter subjects used a standard crouched-position start, similar to that used for the treadmill sprints. The 100-m sprints were performed individually, and performance was measured with a radar system (Stalker ATS System, Radar Sales, Minneapolis MN, USA). This device has been validated and used in previous human sprint running experiments (e.g. Chelly and Denis 2001; Di Prampero et al. 2005; Morin and Sève 2011) and measures the forward running speed of the subject at a sampling rate of 35 Hz. It was placed on a tripod 10 m behind the subjects at a height of 1 m (corresponding approximately to the height of subjects' centre of mass).

To better analyze the 100-m performance, radar speed–time curves were fitted by a bi-exponential function (Morin and Sève 2011; Volkov and Lapin 1979):

$$S(t) = S_{max}\left[e^{((-t+tS_{max})/\tau 2))} - e^{(-t/\tau 1)}\right] \quad (1)$$

$\tau 1$ and $\tau 2$ being, respectively, the time constant for acceleration and deceleration of this relationship, determined by iterative computerized solving. Speed–distance curves were then obtained from these modeled speed–time curves by simple time-integration of modeled speed data. For more clarity, and given the high quality of the bi-exponential fitting of instantaneous radar data (see for instance Morin and Sève 2011), only the modeled speed data were analyzed. From these data, maximal running speed (S-max in m s^{-1}) was obtained, as well as the 100-m time and the corresponding mean 100-m speed (S_{100} in m s^{-1}) for each subject. For the four sprinters, 100-m times were also measured with a pair of photo-cells and a chronometer triggered by a standard audio signal similar to those of typical competitions. Last, to describe the acceleration performance in relation to sports other than track and field, and with a practical and simple index, the 4-s distance (d_4 in m) was measured as the distance covered during the first 4 s of the 100-m.

Anthropometric measurements

Sub-ischial length (L, cm), referred to as leg length was measured as the great-trochanter-to-ground distance in a standing position, measured with 0.5 cm accuracy. To facilitate comparison between subjects, the leg length to standing height ratio (L/H) and body mass index (BMI, kg m^{-2}) were used.

Statistical analyses

All data are presented as mean ± SD. After normality checking by the Shapiro–Wilk test, and in case of normal distribution, correlations between mechanical and performance parameters were tested by means of Pearson's correlation coefficients. In case of absence of normal distribution, the Spearman rank test was used to test these correlations. A P value of 0.05 was accepted as level of significance.

Results

The main field sprint performance (100-m time) recorded during the experiment was 12.73 ± 1.48 s, ranging from 10.35 to 15.03 s. For the world-class and national-level sprinters, these performances corresponded to 95.8 ± 1.6 % of their personal best times. Table 1 shows the main performance and mechanical variables studied.

The results showed a significant correlation between mean and maximal power output measured on the treadmill and the three main 100-m performance variables: S-max, S_{100} and d_4 (Table 2).

All linear F–V regressions were significant (mean r^2 of 0.909, range 0.804–0.982; all $P < 0.001$). We also tested second degree polynomial regressions to model the F–V relationship (data not shown), and the mean r^2 value for the group only slightly increased (to 0.930 ± 0.052). Although this increase was statistically significant, the fact that (1) linear regressions also gave significant and very high r^2 values, and that (2) our analysis and interpretation of the mechanical F–V qualities was based on previous works using a linear approach; we maintained this approach in our study.

The theoretical maximal horizontal GRF (F_H0) was not significantly correlated to any of the performance variables considered, whereas the maximal theoretical running velocity $V0$ was (Table 2). The typical F–V relationships of

Table 1 Main 100-m performance and mechanical variables averaged over the acceleration phase of the sprint on the instrumented treadmill (from the second step until top speed)

Variable	Mean (SD)	Range
Field 100-m sprint performance		
Average 100-m speed (m s^{-1})	7.96 (0.98)	6.65–9.66
Maximal 100-m speed (m s^{-1})	9.32 (1.15)	7.80–11.2
4-s distance (m)	25.1 (3.19)	20.9–31.0
Treadmill sprint kinematics		
Contact time (s)	0.147 (0.019)	0.121–0.181
Aerial time (s)	0.094 (0.011)	0.077–0.121
Step frequency (Hz)	4.17 (0.27)	3.80–4.64
Step length (m)	1.41 (0.15)	1.03–1.56
Swing time (s)	0.330 (0.025)	0.297–0.371
Treadmill sprint kinetics		
Index of force application technique	−0.074 (0.015)	−0.093 to −0.042
Horizontal GRF (N)	240 (37)	201–314
Horizontal GRF (BW)	0.322 (0.048)	0.224–0.398
Vertical GRF (N)	1,235 (183)	981–1,515
Vertical GRF (BW)	1.66 (0.15)	1.48–1.85
Resultant GRF (N)	1,263 (184)	1,009–1,549
Resultant GRF (BW)	1.7 (0.15)	1.52–1.90
Vertical GRF at maximal velocity (N)	1,371 (178)	1,109–1,657
Vertical GRF at maximal velocity (BW)	1.85 (0.14)	1.63–2.07
Treadmill force–velocity characteristics and power output		
Maximal velocity (m s^{-1})	7.05 (0.91)	5.75–8.66
Maximal power output (W kg^{-1})	22.7 (4.88)	16.0–31.1
Mean power output (W kg^{-1})	18.1 (4.26)	11.1–25.5
Theoretical maximal horizontal force (N kg^{-1})	8.61 (1.09)	6.23–10.7
Theoretical maximal velocity (m s^{-1})	9.85 (1.70)	7.71–14.0

Table 2 Correlations between mechanical variables (rows) of the force–velocity relationship and power output and 100-m performance variables (columns)

	Maximal speed (m s^{-1})	Mean 100-m speed (m s^{-1})	4-s distance (m)
Maximal power output	**0.863** (*<0.01*)	**0.850** (*<0.01*)	**0.892** (*<0.001*)
Average power output	**0.810** (*<0.01*)	**0.839** (*<0.01*)	**0.903** (*<0.001*)
Theoretical maximal horizontal force F_H0	0.560 (*0.052*)	0.447 (*0.128*)	0.432 (*0.14*)
Theoretical maximal horizontal velocity *V*0	**0.819** (*<0.01*)	**0.735** (*0.011*)	**0.841** (*<0.01*)

Significant correlations are reported in bold. Values are presented as Pearson's correlation coefficient (*P* values in italics)

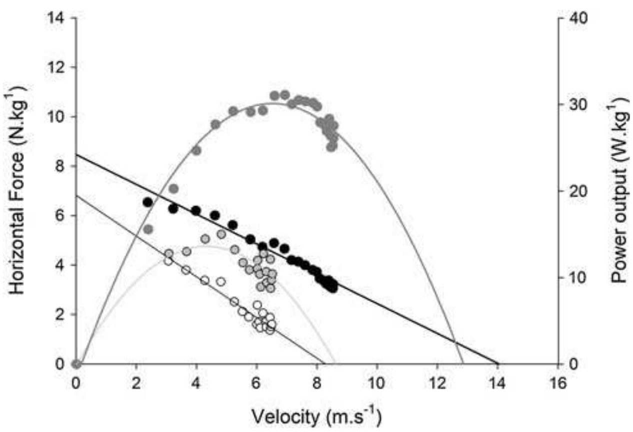

Fig. 1 Typical linear force–velocity and 2nd degree polynomial power–velocity relationships obtained from instrumented treadmill sprint data for the fastest (100-m best time: 9.92 s, 100-m time of 10.35 s during the study: *black and dark grey circles*) and slowest (100-m time of 15.03 s during the study: *white and light grey circles*) subjects of this study. All linear and 2nd degree polynomial regressions were significant ($r^2 > 0.878$; all $P < 0.001$)

Table 3 Correlations between mechanical variables of sprint kinetics measured during treadmill sprints (rows) and 100-m performance variables (columns)

	Maximal speed (m s^{-1})	Mean 100-m speed (m s^{-1})	4-s distance (m)
Index of force application technique D_{RF}	**0.875** (*<0.01*)	**0.729** (*<0.05*)	**0.683** (*<0.05*)
Horizontal GRF	**0.773** (*<0.01*)	**0.834** (*<0.01*)	**0.773** (*<0.05*)
Vertical GRF	**0.593** (*<0.05*)	0.385 (*0.18*)	0.404 (*0.16*)
Resultant GRF	**0.611** (*<0.05*)	0.402 (*0.16*)	0.408 (*0.16*)

Significant correlations are reported in bold. Horizontal, vertical and resultant GRF data are averaged values for the entire acceleration phase. Values are presented as Pearson's correlation coefficient (*P* values in italics)

the fastest and slowest subjects presented in Fig. 1 show their relatively higher difference in *V*0 than in F_H0 values. These two individuals also strongly differed in terms of peak power and optimal velocity, as shown by the comparison of their power–velocity relationships (Fig. 1).

Concerning GRF production and orientation onto the ground, Table 3 shows that D_{RF} index was significantly correlated to all the performance variables considered, contrary to F_{Tot}, which was only significantly correlated to *S*-max ($P = 0.034$). For the components of this resultant GRF, F_H was significantly correlated to 100-m performance ($P < 0.05$), whereas F_V was only correlated to *S*-max ($P = 0.039$), and not to S_{100} or d_4.

These correlations between sprint performance (mean 100-m speed) and F_{Tot} and D_{RF} are shown in Fig. 2.

The ability to orient the resultant GRF vector effectively (i.e. forward) during the acceleration phase on the treadmill (analyzed through the D_{RF} value) strongly differed between the fastest and slowest individuals tested (Fig. 3). In addition to being the individuals presenting the extreme values of 100-m time, they had the highest (−0.042) and second lowest (−0.091) values of D_{RF} of the group.

Contact time and step frequency showed significant and high correlations ($P < 0.01$) with 100-m performance (Table 4), which was also the case of the swing ti me ($P < 0.05$). However, neither aerial time ($P > 0.88$) nor step length ($P > 0.21$) was related to sprint performance.

Last, BMI (23.2 ± 2.2 kg m^{-2}) and L/H ratio (0.522 ± 0.014) were not correlated to any of the performance variables studied (all $P > 0.29$).

Discussion

To our knowledge, since the work of Weyand et al. (2000), this is the only study to specifically report experimental data obtained in a group of subjects ranging from non-specialists to national-level sprinters, and to a sub-10-s athlete. Since pioneering works about human sprint performance published in the late 1920s (Best and Partridge 1928; Furusawa et al. 1927) involving very fast runners (estimated 100-m time of ~10.8 s for subject H.A.R., probably 1928 Olympian sprinter Henry Argue Russel, in the study of Furusawa et al. (1927), many studies involved high-level athletes (e.g. Karamanidis et al. 2011; Mero and

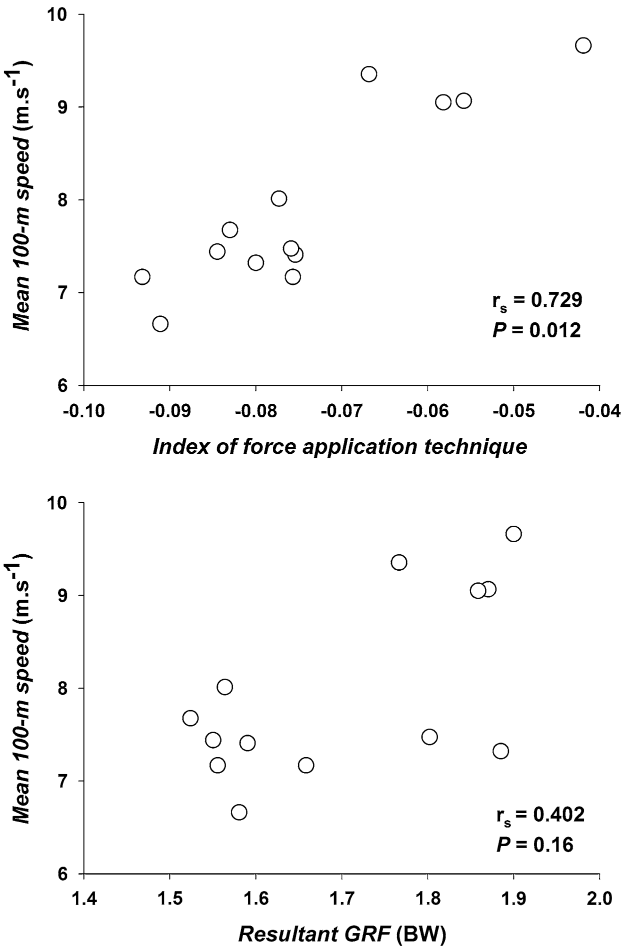

Fig. 2 Correlations between sprint performance parameter of mean 100-m running speed and mechanical variables of index of force application (*left panel*), and resultant ground reaction force (*right panel*) as measured during the 6-s treadmill sprints. r_s Spearman correlation coefficient

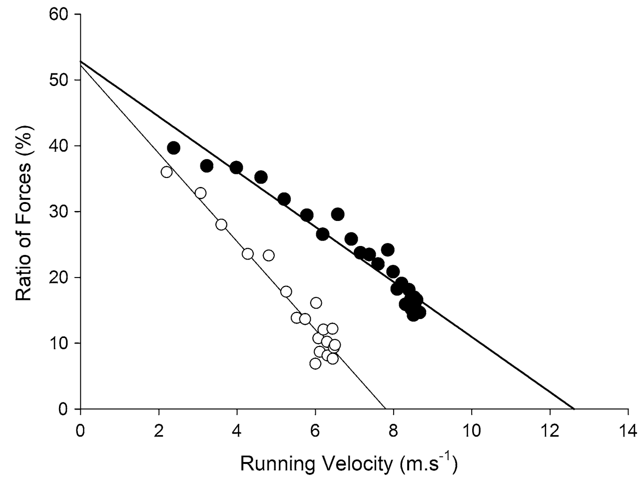

Fig. 3 Typical RF–velocity linear relationships during the acceleration phase of the treadmill sprint for the fastest (100-m best time: 9.92 s, 100-m time of 10.35 s during the study: *black circles*) and slowest (100-m time of 15.03 s during the study: *white circles*) subjects of this study. These linear regressions were significant ($r^2 > 0.936$; $P < 0.001$). Each point represents average values of ratio of forces and velocity for one contact phase

Table 4 Correlations between mechanical variables of sprint step kinematics measured during treadmill sprints (rows) and 100-m performance variables (columns)

	Maximal speed (m s^{-1})	Mean 100-m speed (m s^{-1})	4-s distance (m)
Contact time	**−0.852** (***<0.01***)	**−0.751** (***<0.01***)	**−0.775** (***<0.01***)
Aerial time	−0.018 (*0.95*)	0.773 (*0.88*)	0.002 (*0.99*)
Swing time	**−0.654** (***<0.05***)	**−0.630** (***<0.05***)	**−0.670** (***<0.05***)
Step frequency	**0.897** (***<0.01***)	**0.893** (***<0.01***)	**0.935** (***<0.001***)
Step length	0.363 (*0.21*)	0.337 (*0.24*)	0.212 (*0.46*)

Significant correlations are reported in bold. All mechanical data are averaged values for the entire acceleration phase. Values are presented as Pearson's correlation coefficient (*P* values in italics)

Komi 1986) but not truly world-class individuals. The main results of this study showed a higher importance of the variables associated with velocity rather than force capabilities (see below). As subjects' level of 100-m increased, this was particularly characterized at high running speeds by the increasing ability to orient the resultant GRF generated by the lower limbs with a forward incline, i.e. to produce higher amounts of horizontal net force at each step, and not by increasing the amount of resultant force produced.

During the treadmill sprint tests, we found a significant and clear correlation between 100-m performance and average or maximal mechanical power normalized to body mass in the horizontal direction ($r_s > 0.810$; $P < 0.01$; Table 2). This was expected from previous findings (e.g. Cronin and Hansen 2005; Cronin and Sleivert 2005; Harris et al. 2008; Sleivert and Taingahue 2004), but the present study had the novelty of reporting mechanical power data measured during specific running exercise (Morin et al. 2010), contrary to the previously cited protocols in which power output was assessed during vertical, horizontal or incline push-offs, or cycling sprints (e.g. Morin et al. 2002). When focusing on the two mechanical entities composing power output (i.e. force and velocity) analyzed through the linear F–V relationships, Table 2 and Fig. 1 clearly show that with the increase in overall sprinting ability (i.e. from non-specialists to national-level sprinters to the world-class individual tested), the orientation of the F–V relationship differs more on the velocity axis than on the force axis. The theoretical maximal horizontal GRF (F_H0) calculated from linear F–V relationship was not significantly correlated to any of the sprint performance variables considered (only a tendency at $P = 0.052$ with maximal running speed), whereas the theoretical maximal velocity ($V0$) was (all $P < 0.011$). When comparing the two extreme individuals in terms of 100-m time (10.35 and 15.03 s during the field test of the present study, Fig. 1), their $V0$ values (14.0 vs. 8.28 m s^{-1}, respectively) differed much more than their F_H0 values (8.47 vs. 6.82 N kg^{-1}, respectively). When expressed as force normalized per kg body mass, F_H dimensionally and conceptually corresponds to a forward acceleration that would be the acceleration of the runner should no resistive force applied on him. Indeed, the maximal values reported in Fig. 1 for the fastest sprinter, i.e. ~6 m s^{-2}, are close to those reported by di Prampero et al. (2005) using radar data obtained during field sprints. This result could be interpreted as a higher importance of the relative capability of the neuromuscular system to keep on producing relatively high levels of horizontal force at high and very high velocities, rather than to produce very high levels of maximal force. Since sprint running acceleration depends on mechanical power, and in turn on both force and velocity outputs, further studies should investigate whether and how sprint running performance could be maximized through an optimal combination of force and velocity capabilities, i.e. whether an "individually optimal F–V profile" exists, as recently shown for jumping exercises by Samozino et al. (2012).

This F–V profile characterized by substantially greater horizontal force production at faster velocities can be explained by the ability to produce a greater resultant force magnitude at rapid movement velocities, which may be partly related to favorable intrinsic muscular properties and muscle fiber type (i.e. high proportion of fast-twitch fibers (Baguet et al. 2011; Gollnick and Matoba 1984), but also by the ability to orient the resultant force vector horizontally during sprint acceleration. Indeed, we observed a high and significant correlation between sprint performance and the ability to produce net horizontal force per unit BW F_H (Table 3). Given the much poorer correlation obtained with resultant force production F_{Tot} (only correlated to S-max, and not to S_{100} or d_4; Table 3), the better ability to produce and apply high F_H onto the ground in skilled sprinters comes mostly from a greater ability to orient the resultant force vector forward during the entire acceleration phase, despite increasing velocity. This is illustrated by the index of force application technique D_{RF}, which was significantly correlated to the three main performance parameters tested (all $P < 0.012$; Table 3; Fig. 2).

As shown in the typical comparison between the fastest and slowest individuals of this study (Fig. 3), the RF–velocity linear relationship is overall less steep as level of performance increases from non-specialist to world-class levels. This means that sprint performance was related to the ability to maintain a high RF with increasing speed during the acceleration, which is illustrated by a high D_{RF} index, as proposed by Morin et al. (2011a). The correlation between D_{RF} and 100-m performance (S_{100}) recently shown by Morin et al. (2011a) in a group of sportsmen including three regional-level sprinters finds here a clear confirmation with a more heterogeneous population, including top-level sprinters and a sub-10-s individual.

In their recent study, these authors found that contrary to D_{RF} ($r = 0.779$; $P < 0.01$, Table 2 of Morin et al. 2011a), the resultant force magnitude while sprinting on the treadmill (F_{Tot}) was not related to S_{100} ($r = 0.411$; $P = 0.19$, Table 2 of Morin et al. 2011a). The present results almost exactly match those previously reported: F_{Tot} was not significantly related to S_{100} when pooling the data of all the subjects tested ($r_s = 0.402$; $P = 0.16$, Table 3), whereas D_{RF} was ($r_s = 0.729$; $P = 0.012$, Table 3). Furthermore, the only performance parameter significantly related to the vertical or resultant force production was top speed (Table 3). The significant correlation found here between F_V or F_{Tot} and field 100-m S-max ($r_s = 0.593$ and 0.611, respectively; $P < 0.05$) is consistent with the results of Morin et al. (2011a), and the hypothesis initially put forward by Weyand et al. (2000) that top speed reached in the field is related to the ability to produce high amounts of vertical GRF per unit BW (which these authors measured at top-running velocity on the treadmill).

Consistently with the importance of velocity production capabilities earlier discussed, step kinematics showed a significant positive correlation between step frequency and sprint performance (Table 4), which was not the case of step length. The higher SF measured over the 6-s sprint in subjects with high sprinting skills resulted from a lower t_c and t_{swing} with similar t_a (significant negative correlations with all $P < 0.05$ for the two former variables, no significant correlations for the latter). The significant correlation between t_{swing} and sprint performance (acceleration, mean and maximal 100-m speed) is contradicting the hypothesis of Weyand et al. (2000) that the time to reposition the limbs from one foot contact to another is not a key factor of sprint performance. This may be due to the fact that t_{swing} was considered here over the entire acceleration phase on the treadmill, whereas Weyand et al. only considered the steps at top speed. This fundamental difference in the approaches (only top velocity phase vs. entire acceleration) likely explains why the present study is different and complementary with Weyand et al.'s one.

These step kinematics results also overall support the idea that high running speeds are achieved through reduced contact times (e.g. McMahon and Green 1979; Weyand et al. 2000, 2010). However, it must be kept in mind that (1) the data presented here were obtained on a sprint treadmill, on which lower top speeds are reached compared to field conditions (Morin and Sève 2011), and (2) they are averaged data for the entire 6-s sprints, and not only data averaged for the steps around top velocity. The same applied to values of SL, which were much lower than what is typically measured at top speed on the field (Table 1). That said, we wanted our analysis to focus on the entire acceleration phase of a sprint, and not only to the very specific top-velocity phase hitherto studied by colleagues (e.g. Bundle et al. 2003; Weyand et al. 2000). Although the reliance on step kinematics (and the debated relative importance of SL and SF) has recently been shown as highly individual among elite athletes (Salo et al. 2011), the present study shows in a heterogeneous group a clear tendency (Table 4) toward the importance of t_c, t_{swing} and SF variables.

Last, no correlation was found between the anthropometric variables studied and 100-m performance (all $P > 0.29$). By comparing body mass and stature values for the world's fastest performers at track racing distances from 100- to 10,000-m, Weyand and Davis (2005) observed that BMI increased as running distance decreased, which would allow sprinters to reach the required support force earlier discussed (Watts et al. 2011; Weyand and Davis 2005). We did not find such a tendency in the group studied, and furthermore, it is worth noting that the BMI of the world-class individual tested (22.3 kg m^{-2}) was consistently lower than the value (close to 24.3 $\pm$ 0.3 kg m^{-2}) reported by Weyand and Davis (2005). It will be of interest to follow whether, in this young sprinter, an increase in BMI related to strength training is to be associated with improved performances. Concerning the L/H ratio, the present data do not seem to indicate that long limbs could be a key factor by allowing extended stride length and providing greater forward propulsion (van Ingen Schenau et al. 1994). That said, according to the recent paper of Bejan et al. (2010), the higher ratio observed in populations living in or originating from Western Africa accounts for the domination of these populations on sprint events. This was also proposed by Rahmani et al. (2004), who compared Italian and Senegalese high-level sprinters. The ratio of the world-class individual tested was the second highest of the group (0.538 vs. 0.520 $\pm$ 0.014 for the rest of the group). In association with the functional abilities above discussed, it is likely that his long limbs would provide him a further advantage in sprinting.

One limitation of the present study is that sprint running mechanics were investigated during sprints performed on an instrumented treadmill, and not overground. The literature is not clear as to the fundamental differences between these two conditions (e.g. Frishberg 1983; Kivi et al. 2002). However, the treadmill measurements performed here aimed at quantifying subjects' ability to apply/orient force onto the ground while sprinting, as opposed to reproducing exact field sprint conditions. Consequently, despite a lower performance on the treadmill, but given the significant correlations observed between field and treadmill sprint performances (Morin and Sève 2011), we can reasonably assume that the inter-individual differences observed in physical and technical capabilities did not fundamentally differ between treadmill and track conditions. Finally, we think that the advantage and novelty of being able to continuously measure GRF and RF and compute D_{RF} over the entire acceleration phase of a maximal sprint in such a population outweighs the issue of lower sprint performance.

To conclude, this study including national- and world-class level athletes as well as non-specialists provided qualitative information toward a better understanding of the biomechanical correlates of sprint running performance, and confirmed recent hypotheses of the literature. The main result of the present study is that a higher level of acceleration and overall 100-m performance is mainly associated with (1) a "velocity-oriented" force–velocity profile, likely explained by (2) a higher ability to apply the resultant GRF vector with a forward orientation over the acceleration, and finally (3) a higher step frequency caused by a shorter contact time. Contrastingly, resultant GRF magnitude was not related to acceleration and overall 100-m performance, but only to top running speed. Further studies should focus on the necessity, effectiveness and practical feasibility of training programs/exercises that could develop the key variables of sprint performance put forward, and on the neuromuscular origin of the macroscopic results obtained here about the integrative variables of lower limbs force and velocity outputs.

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