Technical Ability of Force Application as a Determinant Factor of Sprint Performance

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ABSTRACT

MORIN, J-B., P. EDOUARD, and P. SAMOZINO. Technical Ability of Force Application as a Determinant Factor of Sprint Performance. *Med. Sci. Sports Exerc.*, Vol. 43, No. 9, pp. 1680–1688, 2011. **Purpose**: We transposed the concept of effectiveness of force application used in pedaling mechanics to calculate the ratio of forces (RF) during sprint running and tested the hypothesis that field sprint performance was related to the technical ability to produce high amounts of net positive horizontal force. This ability represents how effectively the total force developed by the lower limbs is applied onto the ground, despite increasing speed during the acceleration phase. **Methods**: Twelve physically active male subjects (including two sprinters) performed 8-s sprints on a recently validated instrumented treadmill, and a 100-m sprint on an athletics track. Mean vertical (F_V), net horizontal (F_H), and total (F_{Tot}) ground reaction forces measured at each step during the acceleration allowed computation of the RF as F_H/F_{Tot} and an index of force application technique (D_{RF}) as the slope of the RF–speed linear relationship from the start until top speed. Correlations were tested between these mechanical variables and field sprint performance variables measured by radar: mean and top 100-m speeds and 4-s distance. **Results**: Significant ($r > 0.731$; $P < 0.01$) correlations were obtained between D_{RF} and 100-m performance (mean and top speeds; 4-s distance). Further, F_H was significantly correlated ($P < 0.05$) to field sprint performance, but F_{Tot} and F_V were not. **Conclusions**: Force application technique is a determinant factor of field 100-m sprint performance, which is not the case for the amount of total force subjects are able to apply onto the ground. It seems that the orientation of the total force applied onto the supporting ground during sprint acceleration is more important to performance than its amount. **Key Words:** TOP SPEED, 100-M, POWER, RUNNING, LOCOMOTION MECHANICS

Whether it is a direct (track and field events) or indirect (e.g., team sports) factor of performance, the ability to sprint is a key parameter in many sports and the focus of many training programs. This ability mechanically corresponds to the capability to produce high-to-top speeds and cover given distances in the shortest times possible or conversely to cover the largest distances in a given span. Contrary to cutting movements that are used in some disciplines (e.g., basketball), sprinting predominantly implies accelerating forward on a level ground.

During accelerated runs, a typical support phase is characterized by a braking phase (negative horizontal ground reaction force (GRF)) followed by a propulsive phase (positive horizontal GRF) (e.g., Hunter et al. [13] and Roberts and Scales [29]). Thus, a positive acceleration in the forward direction will result from a positive value of this net (i.e., stance-averaged) horizontal force (F_H), and the higher F_H, the higher the acceleration. Further, it has been shown that high accelerations in running and bouncing bipeds were achieved by increasing the amount of positive horizontal GRF (18,29) and concomitantly decreasing the amount of negative horizontal GRF (29). From this basic standpoint, it seems logical to expect forward acceleration (hence, high F_H application onto the ground) to be a major determinant of field sprint performance. For instance, Hunter et al. (13) showed that the strongest predictor of the sprint velocity measured at the 16-m mark during acceleration (61% of the variance explained) was the relative horizontal impulse.

On the other hand, studies report relationships between the top speed reached during treadmill sprint and mechanical variables, but only at top speed. These protocol designs required subjects to lower themselves onto the running treadmill belt and perform about eight complete steps at increasing steady speeds, until top speed was reached (e.g., Bundle et al. [4] and Weyand et al. [33–35]). Thus, in such protocols, only the flying top speed that could be maintained for a few steps was considered, irrespective of the typically preceding acceleration phase. That said, the authors showed

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Submitted for publication September 2010.
Accepted for publication February 2011.

0195-9131/11/4309-1680/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0b013e318216ea37

that it was very close to the top speed reached in field sprint (5). Using this kind of design, Weyand et al. (35) showed that the support vertical force produced onto the ground per unit body weight (BW) at top speed was a key determinant of this speed. Knowing the determinants of human top speed and its biological limits is of interest. However, in many sports, if not all, athletes almost never reach their actual individual top speed, yet their forward acceleration capabilities are often necessary for successful performance (e.g., in soccer or rugby).

Accelerating body mass and producing forward speed logically requires production of high amounts of F_H. However, during forward acceleration, the human body is in a mechanical situation in which gravitational constraints are such that the total force is predominantly produced in a direction that is not that of their displacement. Therefore, only the horizontal component of the total force is directed forward, and the other component (vertical) can be considered as ineffective in producing forward acceleration, although necessary to keep moving forward (Fig. 1). In pedaling mechanics, where the total force applied onto the pedal has also been analyzed through its components (e.g., Davis and Hull [7]), only one component of the total force (that oriented perpendicular to the crank arm) is propulsive and necessary to the rotation of the drive. Thus, effectiveness of force application in pedaling has been defined as the ratio of this effective force to the total force applied onto the pedal (7,11,28,30). Since then, effectiveness has been related to subjects' pedaling technique (e.g., Dorel et al. [10]) and cycling mechanical efficiency (e.g., Zameziati et al. [36]).

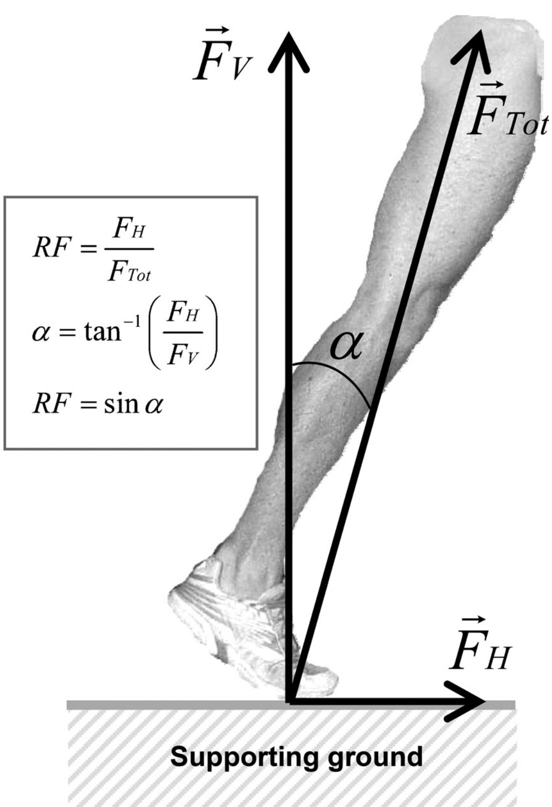

FIGURE 1—Schematic representation of the ratio of forces (RF) and mathematical expression as a function of the total (F_{Tot}) and net positive horizontal (F_H) (i.e., contact-averaged) ground reaction forces. The forward orientation of the total GRF vector is represented by the angle α.

Applying this to sprint running for a given support phase, the mean ratio of forces applied onto the ground (RF) could objectively represent runners' force application technique. This could also be independent from the amount of total force applied, i.e., their physical capabilities. Therefore, we hereby propose to study RF in sprint running, which we define as the ratio of F_H to the corresponding total GRF averaged over the support phase (F_{Tot}). Thus, theoretically, for the same F_{Tot} applied onto the ground over a given stance phase, different strategies of force application (hence, different RF values) may be used and result in different amounts of F_H and, in turn, different net forward accelerations (Fig. 1).

However, contrary to cycling where the aim of a good pedaling technique is to reach maximal RF (i.e., effectiveness of 100%), the necessary vertical component of the total force in running makes it mechanically counterproductive to maximize RF. Indeed, an RF of 100% would mean that the total force is applied horizontally, with no vertical component, making the running motion impossible. Between this implausible maximal RF and RF equal to zero (which theoretically means no net forward acceleration is produced and the total force over the stance is applied vertically), it is not known whether or how RF could be optimized or whether it is related to field sprint performance. Thus, we thought it would be interesting and novel to analyze RF values during sprint acceleration.

To our knowledge, no such approach has been undertaken that would allow calculation of RF over a sprint acceleration phase (and consequently test its potential relationship to field sprint performance). This could be explained by the fact that computing RF requires measurements of the total GRF and both its vertical and horizontal components. To date, some studies performed these measurements using force plates (2,13,16,20,22,23,27), but none reported RF values. That said, some studies reported incline angles of the total GRF vector relative to vertical (16,20), which is mathematically close to the expression of RF proposed here (Fig. 1). These studies suggest that the forward incline angle of the total force vector relative to vertical (and thus RF; Fig. 1) decreases with increasing running speed over a typical sprint acceleration.

The characteristics of this decrease in RF and whether limiting it may enhance field sprint performance are unknown. We hypothesized that the technical ability to limit the decrease in RF with increasing speed would be of interest to sprint performance and used a practical index to characterize subjects' technique of force application measured during maximally accelerated runs. Computing such an index requires GRF measurements during the entire acceleration phase of a sprint, which has never been done to our knowledge, for obvious technical and material reasons.

Indeed, to date, such relationships between force production/application and acceleration/sprint performance have been mainly approached through comparisons between steady-speed (i.e., not accelerated) runs including top speed (e.g., Brughelli et al. [3], Mero and Komi [21], Nummela et al. [27], Weyand et al. [35]). Furthermore, field sprint kinetics have most often been analyzed for three steps or fewer during the starting blocks push-off and/or the first step of the sprint (e.g., Kugler and Janshen [16], Mero [20], Mero et al. [23]), constant-speed runs [21,27], or, more recently, the acceleration phase (~16 m [13]) and around top speed (~45 m [2]). Finally, detailed kinetics of acceleration runs have been studied, and comparisons between different accelerations have been reported in comprehensive animal studies of turkeys (29) and dogs (32).

Thus, to the best of our knowledge, no GRF data are available for the entire sprint acceleration phase of humans. The recent validation of an instrumented treadmill allowing continuous GRF measurements during sprint running (including the typical acceleration phase) from a typical crouched sprint start (25,26) makes it possible to measure both instantaneous horizontal and vertical components of the total GRF and thus calculate RF for each step of a sprint. Indeed, this treadmill allows high-rate samplings of both GRF and belt velocity (25), allowing computation of instantaneous and step-averaged propulsive power and RF. It also allows subjects to adopt a standard sprint-start position and to begin their sprints in a balanced position before their first push-off. Afterward, subjects can sprint ''freely'' because the belt velocity is not preset and depends on subjects' actions, especially their horizontal force production (see ''Methods'' section).

Our aim was therefore to use this recently validated instrumented treadmill to (i) quantify RF and its changes with increasing speed over an entire sprint acceleration phase (from null to top speed) and (ii) investigate the relationships between these technical characteristics of sprint motion and field sprint performance during a 100-m maximal sprint (thereafter named 100 m).

Given the expected importance of the horizontal component of the total force runners apply onto the ground, our main hypothesis was that RF is a key factor of sprint performance. This would represent the technical ability to orient the total GRF vector forward compared with the absolute value of total GRF, which corresponds to the physical capabilities of athletes. This point has recently been suggested by Kugler and Janshen (16), who showed that faster runners were applying more forward-oriented, but not greater, forces against the ground, although the authors analyzed only one running step for each of their subjects' runs. In terms of RF, this would mean that better sprinters have a higher RF over the acceleration phase for a similar amount of total force. This hypothesis, on the basis of mechanical reasoning about forward speed production, is already known and used in practice by many sprint coaches but has hitherto not been supported by experimental data.

METHODS

Subjects and experimental protocol. Twelve male subjects (body mass (mean ± SD) = 72.4 ± 8.6 kg, height = 1.76 ± 0.08 m, age = 26.2 ± 3.6 yr) volunteered to participate in this study. All subjects were free of musculoskeletal pain or injuries, as confirmed by medical and physical examinations. They were all physical education students and physically active and had all practiced physical activities including sprints (e.g., soccer, basketball) in the 6 months preceding the study. Two subjects were national-level long jump competitors (100-m personal bests of 10.90 and 11.04 s). Written informed consent was obtained from the subjects, and the study was approved by the institutional ethics review board of the Faculty of Sport Sciences and was conducted according to the Declaration of Helsinki II.

The protocol consisted in performing one 8-s treadmill sprint and one 100 m on a standard synthetic track. The two sprints, which were performed in a randomized and counterbalanced order, were separated by 30 min of passive rest and performed in similar ambient conditions. Subjects wore the same outfit and shoes in both conditions (no athletics spikes used). About 1 wk before the testing session, subjects undertook a familiarization session during which they repeated treadmill sprints until being comfortable with the running technique required (this took between 10 and 20 short sprints). For the testing session, the warm-up consisted of 5 min of 10 $km \cdot h^{-1}$ running, followed by 5 min of sprint-specific muscular warm-up exercises, and three progressive 6-s sprints separated by 2 min of passive rest. Subjects were then allowed ~5 min of free cool-down before the treadmill sprint. The warm-up preceding the 100 m consisted of repeating the last part of the warm-up (from the three 6-s sprints on).

Mechanical variables. The motorized instrumented treadmill (ADAL3D-WR; Medical Development, HEF Tecmachine, Andrézieux-Bouthéon, France) used has been recently validated for sprint use (for full details, see Morin et al. [25]). 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 the subject's BW. The default torque was measured by requiring the subject to stand still and by increasing the driving torque value until observing a movement of the belt >2 cm during 5 s. This default torque setting as a function of belt friction is in line with previous motorized treadmill studies (6,12,14,15) and with the detailed discussion by McKenna and Riches (19) in their recent study comparing ''torque treadmill'' sprint to overground sprint. Motor torque of 160% of the default value was selected after several preliminary measurements (data not shown) comparing various torques because (i) it allowed subjects to sprint in a comfortable manner and produce maximal effort without risking loss of balance and (ii) higher torques (180% and 200%) caused loss of balance in some subjects. The latter phenomenon prevented them, even after familiarization, to sprint with the same technique as on the track.

Subjects were tethered using a leather weightlifting belt and 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 required to lean forward in a typical crouched sprint-start position (standardized for all subjects and close to that in the field) with their preferred foot forward. After a 3-s countdown, the treadmill was released, and the belt began to accelerate as subjects applied a positive horizontal force. On both the track and the treadmill, subjects were encouraged throughout the sprint.

Mechanical data were sampled at 1000 Hz throughout the sprint, allowing determination of the beginning of the sprint, defined as the moment the belt speed exceeded 0.2 m·s^{-1}. After appropriate filtering (Butterworth-type 30-Hz low-pass filter), instantaneous values of GRF and belt speed were averaged for each contact period (vertical force >30 N), which corresponds to the biomechanical/muscular specific event of one leg push (1,17).

Instantaneous data of vertical, horizontal, and total GRF were averaged for each support phase (F_V, F_H, and F_{Tot}, respectively), expressed in newtons and BW and used with the corresponding average belt speed (S, m·s^{-1}) to compute net horizontal power ($P_P = F_H S$, W·kg^{-1}). These running kinetics were completed by measurements of the main step kinematic variables: contact time (t_c, s), aerial time (t_a, s), step frequency (f, Hz), and swing time at top speed (t_{swing}), i.e., the time to reposition the limb, from take-off to touchdown of the same foot. Finally, F_V was specifically averaged for the five steps around top speed on the treadmill and reported as $F_{V\text{–}S\mathrm{max}}$.

Ratio of forces and index of force application technique. For each step, RF (%) was calculated as the mean ratio of F_H to F_{Tot} for one contact period. The angle of orientation of the F_{Tot} vector with respect to vertical could therefore be calculated as $\alpha = \sin^{-1}\mathrm{RF}$ (Fig. 1). Furthermore, RF for the very first step (i.e., at very low forward speeds) was expected to be high (crouched position when attached backward to a fixed point) and then to decrease with acceleration. Indeed, at the end of the acceleration (i.e., at top speed), RF was expected to be close to zero (no net forward acceleration). Therefore, we calculated an index of force application technique (D_{RF}) representing the decrement in RF with increasing speed. Because with increasing speed, the overall inclination of the body was expected to approach vertical (9), D_{RF} was computed as the slope of the linear RF–speed relationship calculated from step-averaged values between the second step and the step at top speed (Fig. 2B). Therefore, the higher the D_{RF} value (i.e., a flat RF–speed relationship), the more RF is maintained despite increasing velocity. Conversely, subjects with a low D_{RF} (i.e., a steep RF–speed relationship) were those who had the highest decreases in RF with increasing speed. To summarize these two concepts, RF represents the part of F_{Tot} that is directed forward, and D_{RF} indicates how runners limit the decrease in RF with increasing speed during an acceleration run (or conversely how they maintain RF to produce high amounts of F_H during their acceleration).

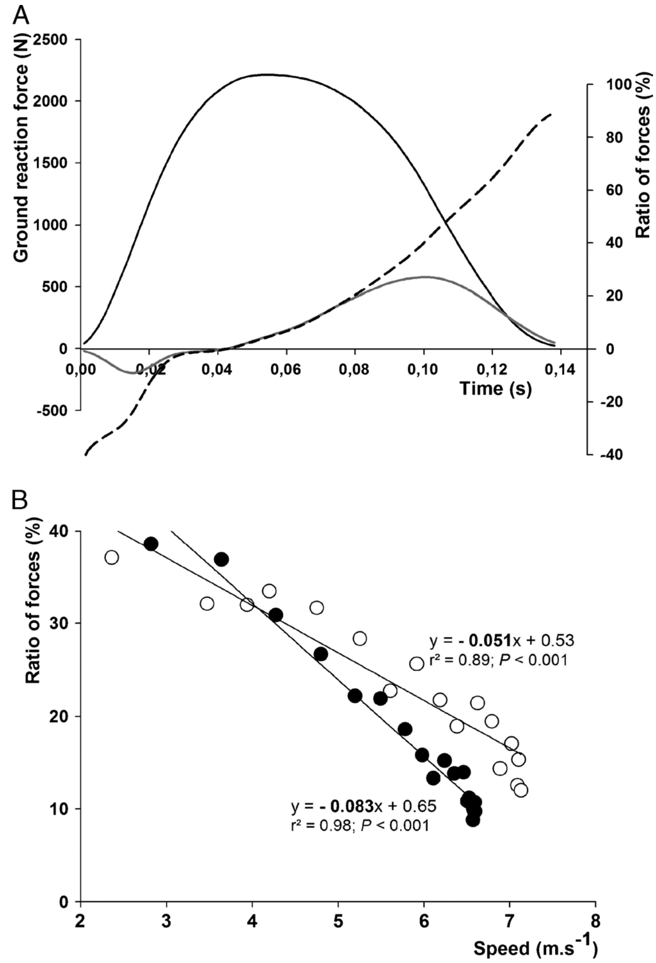

FIGURE 2—A, Typical traces of vertical (*black line*) and horizontal (*gray line*) GRF and of RF (*dotted black line*) during the support phase of a sprint step. This typical example (subject 11, body mass = 68.1 kg) corresponds to the 10th step of the sprint, for which top speed was reached after 17 steps. Mean values of F_H, F_V, and RF for this step were 195 N, 1348 N, and 19.6%, respectively. This value of mean RF corresponds to a forward inclination angle of α = 11.3°. B, Linear relationship between RF and speed during the acceleration phase of the treadmill sprint (from the second step and the step at top speed) for subjects 2 (*black circles*) and 11 (*white circles*). Each point corresponds to values of RF and running speed averaged for one contact phase. Despite similar initial maximal values of RF, their D_{RF} (i.e., the slopes of their respective RF–speed relationships) differed strongly: −0.051 for subject 11 and −0.083 for subject 2.

Field sprint performance. The 100-m sprints were performed from a standing start (crouched position similar to that on the treadmill), and performance was measured using a radar Stalker ATS System™ (Radar Sales, Minneapolis, MN), which has been validated and used in previous human sprint running experiments (6,9,24,26), to measure the

TABLE 1. Ratio of forces, index of force application technique, and main 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
Maximal value of RF (%)	37.6 ± 4.22	28.9 to 42.4
Mean value of RF (%)	19.9 ± 2.98	13.9 to 23.7
Mean 4-s RF (%)	21.8 ± 2.78	16.6 to 25.0
Index of force application technique (D_{RF})	−0.071 ± 0.01	−0.083 to −0.051
Ground reaction forces		
F_H (BW)	0.322 ± 0.056	0.224 to 0.411
F_H (N)	225 ± 27	184 to 275
F_V (BW)	1.62 ± 0.14	1.45 to 1.85
F_V (N)	1144 ± 150	915 to 1465
F_{Tot} (BW)	1.65 ± 0.14	1.49 to 1.89
F_{Tot} (N)	1170 ± 151	937 to 1484
F_V at top speed (BW)	1.79 ± 0.16	1.59 to 2.10
F_V at top speed (N)	1267 ± 153	1001 to 1554
P_P (W·kg^{-1})	16.5 ± 3.18	11.1 to 22.4
S_{max} (m·s^{-1})	6.61 ± 0.45	6.75 to 7.34
Contact time (s)	0.153 ± 0.016	0.127 to 0.181
Aerial time (s)	0.094 ± 0.013	0.077 to 0.121
Step frequency (Hz)	4.11 ± 0.27	3.80 to 4.69
Swing time (s)	0.350 ± 0.025	0.312 to 0.383

forward speed of the runner 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' CM).

From these measurements, speed–time curves were plotted (6,9,24,26), and maximal running speed (S_{max}, m·s^{-1}) was obtained, as well as the 100-m time (t_{100}, s) and the corresponding 100-m mean velocity (S_{100}, m·s^{-1}). 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, m) was measured as the distance covered during the first 4 s of the 100 m.

Data analysis and statistics. Descriptive statistics are presented as mean values ± SD. Normal distribution of the data was checked by the Shapiro–Wilk normality test. Our hypothesis was tested using Pearson correlation computed between experimental variables measured on the treadmill and field performance variables measured during the 100 m. Individual RF–speed relationships were described by linear regression calculated from step-averaged values, from the second step (we did not take the very first push-off into account because it was not a complete push-off) to the step at top speed. Further, a mean RF value was calculated for the first 4 s of the treadmill sprint to correspond to the performance variable d_4 and describe the early phase of the sprints. The significance level was set at $P < 0.05$.

RESULTS

The RF–speed relationships were linear for all subjects (r^2 ranging from 0.707 to 0.975; $P < 0.05$). The maximal and mean values of RF for the acceleration phase of the treadmill sprints are shown in Table 1, along with values of D_{RF} and mechanical variables of the sprints.

On the track, subjects ran the 100 m in 13.40 ± 0.85 s (range = 11.90–15.01 s), which corresponded to S_{100} = 7.48 ± 0.48 m·s^{-1}, for a top speed of 8.79 ± 0.59 m·s^{-1} (range = 7.80–9.96 m·s^{-1}). The 4-s distance was 23.6 ± 1.9 m (range = 20.9–26.3 m). Table 2 and Figure 3 show the main relationships between mechanical variables and field sprint performance over the 100 m. The index of force application technique, D_{RF}, was significantly related to the three main 100-m performance parameters: S_{max}, S_{100}, and d_4 ($r > 0.735$, $P < 0.01$), as were the mean 4-s RF ($r > 0.689$, $P < 0.05$) and the mean value of F_H over the acceleration ($r > 0.621$, $P < 0.05$). Contrastingly, neither F_V nor F_{Tot} averaged over the acceleration phase was related to these performance parameters. An exception to this result was when F_V was computed specifically at top speed on the treadmill: $F_{V\text{–}S\max}$ was significantly correlated ($r = 0.612$, $P < 0.05$) to the top speed reached on the track.

Finally, subjects' capabilities to apply high amounts of total force onto the ground, as quantified by F_{Tot} per unit BW, was not significantly correlated to any calculated indices of force application technique: mean RF ($P = 0.68$), D_{RF} ($P = 0.25$), or mean 4-s RF ($P = 0.26$).

DISCUSSION

The main result of this study is that the force application technique, and more precisely the ability to limit the decrease in RF during accelerated runs on a sprint treadmill despite the increasing speed, was highly ($P < 0.05$) correlated to field 100-m performance (4-s distance, 100-m top, and mean speeds). This was not the case for total force produced. Thus, the way runners apply force onto the ground (technical ability) seems to be more important to field sprint performance than the amount of total force they are able to produce (physical capability), confirming our hypothesis (at least for the population tested). Net positive horizontal force and power as measured on the instrumented sprint treadmill were also significantly ($P < 0.05$) correlated with the field sprint performance variables S_{max}, S_{100}, and d_4. Further, S_{max}

TABLE 2. Correlations between mechanical variables (rows) and 100-m performance variables (columns).

	Maximal Speed (m·s^{-1})	Mean 100-m Speed (m·s^{-1})	4-s Distance (m)
Maximal value of RF (%)	0.013 (0.97)	−0.018 (0.96)	−0.217 (0.96)
Mean 4-s RF (%)	**0.695 (<0.01)**	**0.773 (<0.01)**	**0.689 (<0.05)**
Index of force application technique (D_{RF})	**0.735 (<0.01)**	**0.779 (<0.01)**	**0.745 (<0.01)**
F_H (BW)	**0.775 (<0.01)**	**0.736 (<0.01)**	**0.621 (<0.05)**
F_V (BW)	0.501 (0.10)	0.390 (0.22)	0.466 (0.13)
F_{Tot} (BW)	0.520 (0.08)	0.411 (0.19)	0.471 (0.13)
F_V at top speed (BW)	**0.612 (<0.05)**	0.507 (0.09)	0.498 (0.10)
P_P (W·kg^{-1})	**0.891 (<0.001)**	**0.862 (<0.001)**	**0.715 (<0.01)**

F_H, F_V, F_{Tot}, and P_P are mean values for the acceleration phase. Values are presented as Pearson correlation coefficient (P values). Significant correlations are reported in bold.

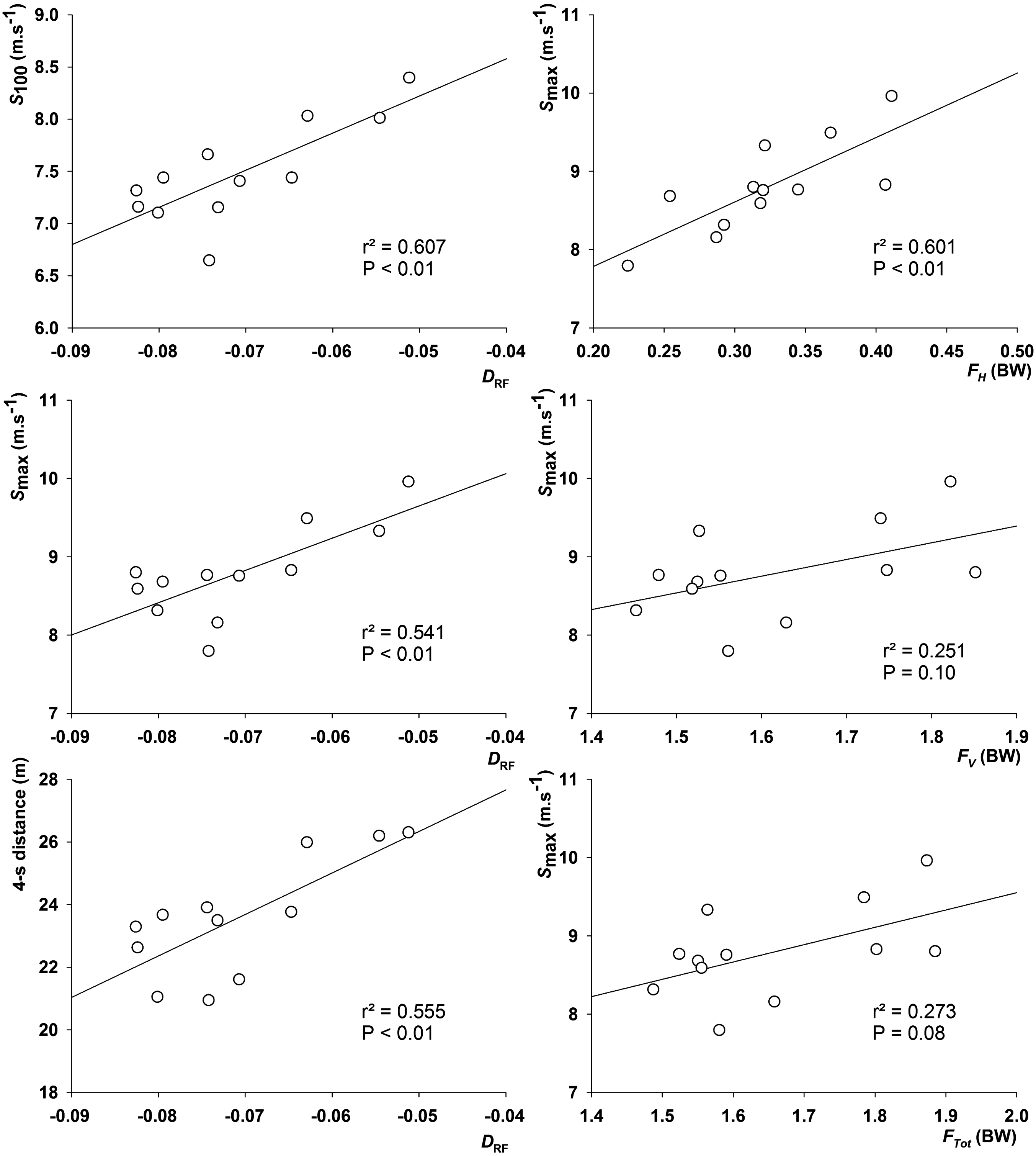

FIGURE 3—Linear regressions between field and treadmill performance parameters of index of force application technique, D_{RF} (*left panels*) and horizontal, vertical, and total GRF (*right panels*). The linear regressions between F_V and S_{max} and between F_{Tot} and S_{max} were not significant.

was only significantly ($P < 0.05$) related to the vertical force per unit BW applied onto the ground when the latter was measured specifically at S_{max} on the treadmill and not when averaged during the entire acceleration phase ($P = 0.100$).

The comparison of RF and D_{RF} data with previous studies is limited because, to our knowledge, this study is the first to present such data. That said, the values of RF reported here are consistent with those that could be estimated from total GRF vector angle and horizontal and vertical components of GRF reported in previous studies (because RF equals the sine of this angle). For instance, at the first step of a maximal acceleration from a standing start, Kugler and Janshen (16) reported a forward orientation of the maximal ground reaction force vector of 22° from the vertical. This angle would correspond to a RF value of ~37.5%. This is very close to the maximal RF values reported in the present study (Table 1). Further, RF as computed in the present study (i.e., from net forces) can be compared with RF estimated from corresponding data in the literature. For instance, from the average values of horizontal and vertical forces and impulses during braking and pushing phases measured for the first contact after the blocks in eight sprinters (Table 3 in Mero [20]), the calculated net horizontal and vertical forces were ~325 and 288 N, respectively. This corresponds to an estimated total force of ~434 N and an RF of ~74.9%. Our maximal values of RF are well in line with those of Kugler and Janshen (16) but far below those of Mero (20). This could be explained by the fact that, contrary to our study and that of Kugler and Janshen (16), subjects did not take a standing start in a crouched position. Instead, subjects used starting blocks, which likely allowed them to apply a more forward-oriented force onto the ground at their first step, hence the much higher estimated RF. Finally, our values of F_V, F_H, and F_{Tot} (maximal, mean for the acceleration phase, or at top speed) are in line with previous human sprinting studies (16,20,25,34,35).

The main originality of our approach is that, contrary to previous studies in which RF could be estimated for only a very limited number of steps during a sprint (most of the time one or two), the instrumented treadmill used here allowed calculation of RF for each step and, consequently, accurate study of its continuous changes with increasing running speed. This is, in our opinion, a novel and direct way to approach acceleration capabilities compared with previous protocol designs (see introduction). Further, it allowed proposal and computation of D_{RF}, which represents the ability of runners to produce and maintain optimal values of RF over the entire acceleration, despite the overall straightening up of their body with increasing speed.

This decrease in RF with increasing speed has also been observed in cycling, where subjects could not maintain high values of force effectiveness when pedaling frequency increases (10,30). Therefore, we think that D_{RF} (the slope of the RF–speed relationship) is a better index of the technical ability of runners to apply force effectively onto the ground over the entire acceleration phase than mean or maximal RF. Indeed, maximal RF is measured at the first or second step of the sprint and is less representative of the entire acceleration than D_{RF}. Maximal RF may also be related to/caused by the overall geometric configuration of the standing start on the treadmill: subjects are attached at the same location (their waist and the wall anchor, 2 m behind them), and the maximal angle they can achieve in a crouched position (and thus their maximal RF) may not be totally independent of the geometric constraints this method. However, D_{RF} depends on the ability to orient total force at each step and is closely linked to overall sprint training background (the sprint-trained subjects demonstrated the best D_{RF} values). Therefore, we can reasonably hypothesize that training this ability to limit the loss of RF during an acceleration phase could be useful to improve sprinting skills.

Indeed, as expected, our results show that net horizontal power output is a mechanical variable strongly related to field 100-m sprint performance (be it quantified through S_{max}, S_{100}, or d_4). However, the total force, F_{Tot}, was not significantly related to these performances (Table 2), whereas the force application technique (be it represented by the mean 4-s RF or D_{RF}) and the horizontal force were ($P < 0.05$; Table 2). It must be noted that the maximal possible value of RF (i.e., ~100%) is not ideal because it precludes the running motion, which requires a certain amount of vertical force to be applied onto the ground. Further, the maximal reported values of RF (i.e., ~38% at the first or second steps) were not correlated with performance. Because it is not feasible to maximize initial RF values, further studies could investigate individual optimum values of RF, if an optimum exists.

Contrary to F_V (which is an average value for the entire acceleration phase), the amount of vertical force per unit BW applied onto the supporting ground specifically measured at top speed on the treadmill ($F_{V\text{–}Smax}$) was significantly linked to track S_{max} ($P < 0.05$; Table 2). This confirms results of Weyand et al. (35) who showed a similar significant relationship between $F_{V\text{–}Smax}$ and S_{max} ($r^2 = 0.39$, $P = 0.02$, n = 33 vs $r^2 = 0.38$, $P = 0.03$, $n = 12$ in the present study), yet for a much wider range of top speeds (6.2–11.1 vs 7.80–9.96 m·s^{-1}). Further, as also reported by Weyand et al. (35), we did not observe a significant correlation between t_{swing} and S_{max} ($r^2 = 0.04$, $P = 0.56$), confirming their hypothesis that vertical force per unit BW produced at top speed is a determining factor of top speed (here on the track during the 100 m) rather than the ability to quickly reposition the lower limbs at each step. Our results confirm those of Weyand et al. (35) that applying a high amount of vertical force per unit BW at the moment top speed is reached is necessary to run at a high S_{max}. However, this may be mechanically counterproductive when trying to increase forward speed during the overall acceleration phase of a sprint. Indeed, during the acceleration phase, our results show that F_H is a key variable but not F_V.

The 100 m has often been described as a three-component race: acceleration phase, approximately constant top speed phase, and deceleration phase (8,22,31). Our results support the fact that net horizontal force and power, partly influenced by subjects' force application technique, are significantly related to performance in the acceleration phase. Further, they confirm that top speed is significantly related to the ability of subjects to apply high amounts of vertical GRF onto the supporting ground when running at top speed. Factors associated with performance during the deceleration phase remain to be thoroughly investigated. In a previous study (24), we proposed the hypothesis that the capability to maintain overall lower limb stiffness despite fatigue in sprint running was related to sprint performance in fatigue conditions based on results obtained over repeated 100 m. This hypothesis could be transposed to a single 100 m during which the systematically observed decrease in speed could be explained by changes in the overall capability of athletes to run with high values of lower limb stiffness or at least to maintain this stiffness over the last two phases of the 100 m. It is interesting to note that RF, D_{RF} and P_P measured during treadmill acceleration were significantly related not only to field S_{max} and d_4 but also to overall field 100-m performance (Table 2).

This study shows that the technical ability of sprinters, represented by RF and D_{RF}, rather than their capability to produce total force (F_{Tot}), is related to acceleration (d_4) and overall field 100-m (S_{100} and S_{max}) performance. These two parameters correspond to different and independent capabilities and should therefore be the focus of specific training programs and exercises. The fact that these parameters are distinct is supported by the absence of significant correlation between F_{Tot} and calculated indexes of force application technique (mean or maximal RF, 4-s RF, or D_{RF}).

A good example of the distinction between the technical and physical capabilities put forward in this study is that of the two typical subjects presented in Figure 2B. Subject 11 is a national-level long jumper, has been training for sprint and long jump for about 10 yr, and has a personal best of 10.90 s in the 100 m. Subject 2 is a basketball and mountain bike competitor and not specialized in sprint. These two subjects have about the same body mass (68.1 vs 69.9 kg) and similar values of maximal RF (Fig. 2B). Further, their capabilities of total force production over the acceleration phase were very close: F_{Tot} = 1.87BW for subject 11 and 1.89BW for subject 2. However, their D_{RF} (−0.051 vs −0.083) were the two extreme values for the population tested. This means that subject 11 was able to maintain much higher values of RF when accelerating compared with subject 2, despite similar RF at the first step. What is interesting and clearly illustrates the superior 100 m of subject 11 (S_{max} of 9.96 vs 8.80 m·s^{-1}, t_{100} of 11.90 vs 13.66 s, and d_4 of 26.3 vs 23.3 m) is that despite similar total force production capabilities, he had a better D_{RF} during treadmill accelerated runs.

A limit of the present study is that we did not observe RF values reaching zero as subjects reached their top speed on the treadmill (Fig. 2B), which should have theoretically been the case. Further, top speeds reached on the treadmill were lower than those on the track (6.61 ± 0.45 vs 8.79 ± 0.59 m·s^{-1}). This is because friction forces and overall inertia of the treadmill system require subjects to produce a low but not null amount of net horizontal force at each step to maintain a nearly constant top speed. Indeed, we estimated the net horizontal force production during the field 100 m from speed–time curves, forward acceleration as a function of time, and basic laws of dynamics (26). The results show that the difference between measured (treadmill) and estimated (field) F_H was 69.9 ± 8.5 N on average for the group over the acceleration phase of the 100 m (i.e., from start to S_{max}). Further, individual differences in F_H between field and treadmill conditions computed over the 100 m were significantly correlated with corresponding values of mean F_V per unit BW (r = 0.69, P = 0.023) and not with subjects' body mass or treadmill F_H, S_{max}, contact time, aerial time, or step frequency. These data clearly support the hypothesis that the differences in force production between treadmill and track are linked to mechanical variables representing the intensity of subjects' vertical actions against the belt rather than to the amounts of F_H produced.

This limit may not fundamentally challenge the proposed calculation of D_{RF}. As may be observed in Figure 2B, and as mentioned above, the right parts of RF–speed linear regressions do not reach null values of RF (y axis) or top speeds similar to those observed in the field (x axis), i.e., 8.79 ± 0.59 m·s^{-1}. Given that (i) D_{RF} is computed as the slope of this linear relationship and (ii) this linearity is significant and clear for all subjects for the range of RF and speeds tested on the treadmill (i.e., up to 6.61 ± 0.45 m·s^{-1} on average), it is very likely that if the treadmill had allowed subjects to reach top speeds equivalent to those on the track (through reduced resistance), D_{RF} values would have been very close to those reported. To support this assumption, we compared theoretical treadmill top speed values (x axis intercept obtained by extrapolation of the linear RF–speed relationship; Fig. 2B) to field S_{max} for each individual. The values were very close (8.53 ± 0.84 m·s^{-1} on the treadmill vs 8.79 ± 0.59 m·s^{-1}) and highly correlated (r = 0.899, P < 0.001). Consequently, it is likely that the RF–speed relationship in the incomplete bottom right part of Fig. 2B would follow the observed linearity of the data measured, and thus that the slope (i.e., D_{RF}) would be similar.

That said, the treadmill measurements aimed at quantifying subjects' ability to apply/orient force onto the ground while sprinting at their maximum, as opposed to reproducing exact field sprint conditions. Consequently, despite a lower running speed on the treadmill, we can reasonably hypothesize that the interindividual differences observed in physical and technical capabilities did not fundamentally differ between treadmill and track conditions. Data obtained on 11 of the present 12 subjects showed that the performance parameters studied (100-m times and top speeds included) were significantly correlated between the two conditions (n = 11, r > 0.63, P < 0.05) (26). Finally, the main step kinematics (t_c, t_a, t_{swing}, and f) observed in the present study were in accordance with those reported at similar speeds during maximal-speed treadmill sprinting (e.g., Weyand et al. [33–35]). Therefore, we think that, despite the lower performance observed on the treadmill, the overall sprint mechanical pattern was not fundamentally altered. Thus, 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 outweighs the issue of lower top speed values.

In conclusion, ground reaction force measurements during treadmill sprinting allowed calculation of an index of force application technique and to show that it was significantly correlated to field 100-m performance. This was not the case for the amount of total force per unit BW the subjects were able to produce. In other words, it seems that the importance is not so much the amount of total force produced, but the way it is oriented onto the supporting ground during the acceleration phase of the sprint. Because this may be considered a technical ability, further studies should investigate whether it could be trained/improved, by what practical means, and whether the training exercises typically used by coaches to train athletes to ''push forward for a greater distance'' actually and efficiently do so.

No funds were received for this study from National Institutes of Health, Wellcome Trust, Howard Hughes Medical Institute, or others.

The authors sincerely thank Dr. Peter G Weyand, from Southern Methodist University, Dallas, TX, for his helpful and stimulating comments on their work and on the present article. The authors are also grateful to John "indeed" Temesi, from the Laboratory of Exercise Physiology, University of Saint-Etienne, France, for English-language assistance.

The authors declare that they have no conflict of interest.

The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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