# New Insights Into Sprint Biomechanics and Determinants of Elite 100m Performance

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### by Jean-Benoit Morin, Pascal Edouard and Pierre Samozino

## ABSTRACT

*The laws of mechanics dictate that accelerating body mass in the forward direction requires sprinters to produce force, but also to apply it to the ground in order to generate as much horizontally-oriented ground reaction force (GRF) as possible. Although theoretically obvious, this principle has hitherto not been confirmed by experimental measurements, especially in top-level athletes. The authors used a motorised instrumented treadmill and other techniques to study the relationships between 100m performance and running mechanics, with a specific focus on GRF (resultant, vertical and horizontal components) production and application, in sport science students, national-class sprinters and a world-class performer. They found that the amount of horizontal GRF produced during maximal treadmill sprints is highly correlated to 100m performance, and that how the resultant GRF is applied also correlates to 100m performance. Specifically, they show the importance of horizontally-oriented force versus vertically-oriented force or total force production in the acceleration phase, raising the question of increased use of horizontal force production exercises to improve overall sprinting performance. This project received the top prize in the coaching category of the 2012 European Athletics Innovation Awards.*

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## Introduction

Performance in the sprint events depends to a large extent on the athlete's ability to accelerate his/her mass and generate a high running velocity in the forward direction. To do so, the neuromuscular system, and especially that of the trunk and lower limbs, generates force and this in turn is applied to the ground during the support phase of the running stride cycle, i.e. during the short (≈100 ms or less in top sprinters) contact between the foot (mostly the forefoot) and the ground on each step.

While the ability to achieve a high running velocity and performance during the phase of constant maximal running velocity have been clearly related to the ability to generate a high level of ground reaction force (GRF) in the vertical direction, and is known to be limited by contact duration[1,2], much less is known about the determinants of performance during the acceleration phase of a sprint race. However, this phase represents 60 to 70% of the time it takes top-level athletes to run the entire race in the 100m and an even greater percentage of the shorter indoor sprints (50 or 60m). Therefore, understanding the mechanical determinants of acceleration, as well as overall sprint performance, and particularly the magnitude and orientation of the ground reaction forces, is of great interest to coaches and athletes.

Coaching practice has long considered the capacity for force production to be an inherent feature of acceleration and sprinting ability. How much force and impulse athletes are able to produce, how hard they can "push with a forward incline" or "push the ground" from the starting blocks, during the first and second stances and throughout the entire acceleration phase, is without doubt a key variable in sprint performance. Most sprint-specific training is in fact dedicated to developing or maintaining this capability.

From a purely biomechanical standpoint, moving the centre of mass (CM) (and in turn the entire body) in the forward direction requires propelling it through the application of force onto the supporting ground, the impulse strength of which will determine the amount of change in the velocity of the CM (Newton's law of motion). Following this basic principle, sprinters have two theoretical possibilities to generate greater levels of forward acceleration and running velocity: apply high amounts of resultant (i.e. total) GRF, and/or orient this resultant GRF with a forward orientation. Indeed, the more forward the orientation of the resultant GFR applied, the greater the forward (horizontal) component of the GRF and the lower the vertical component (Figure 1). Mathematically, for a given amount of GRF, the angle of the resultant GRF vector determines the values of the horizontal and vertical components of the resultant GRF. These two components will cause the forward horizontal and vertical accelerations of the CM, respectively.

Although a certain amount of vertical GRF is needed to simply stand upright and make the running motion possible, the intensity of the forward acceleration will mainly depend on the amount of horizontal net GRF applied to the ground at each step. As previously proposed in pedalling mechanics[3-7], the ratio of the efficient component of the resultant force to this resultant force may be considered an index of the "mechanical effectiveness of force application". As shown in Figure 1, the angle with which the resultant force (i.e. the overall force output resulting from all propulsive actions of the lower limbs muscles involved) is applied onto the pedal determines how much efficient (i.e. perpendicular to the crank arm) force and how much inefficient force are produced during each pedal rotation. We used the analogy with the mechanical effectiveness described in pedalling mechanics to propose the effectiveness of force application / orientation in sprint running.

In Figure 1, we define the ratio of force (***RF***) as the ratio of the contact-averaged horizontal force $F_{Hzt}$ to the corresponding resultant GRF ($F_{Tot}$). Thus, theoretically, for the same $F_{Tot}$ applied onto the ground during a given stance phase, different strategies of force application (hence, different ***RF*** values) may be used and result in different amounts of $F_{Hzt}$. We therefore hypothesized that ***RF*** could objectively represent athletes' force application techniques, and that it could also be independent from the amount of total force applied, i.e., their physical capabilities. However, the main limitation we faced here was that measuring ***RF*** for each step of an acceleration phase (typically 40 to 60 or even 70m depending on the level of the

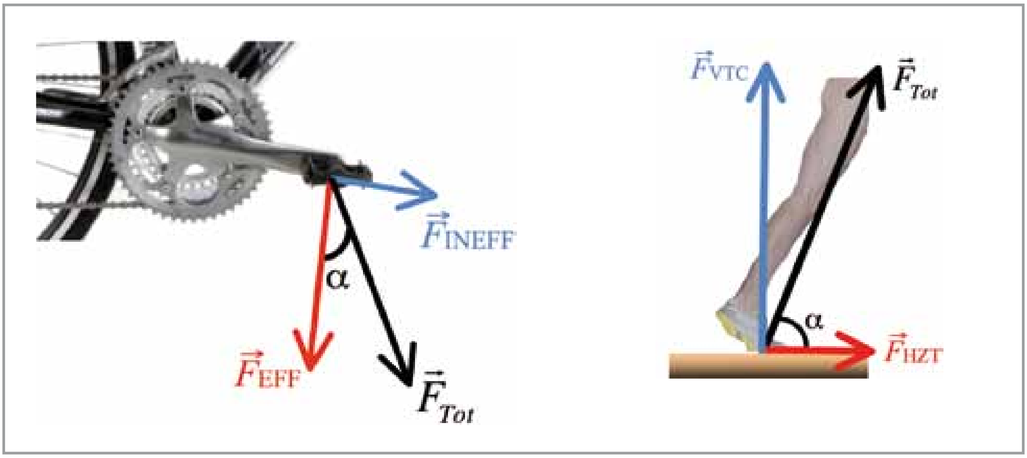


*Figure 1: Effectiveness of force application: from pedalling to sprint running mechanics*

*The mechanical concept of force application effectiveness is a simple ratio. In pedalling (left)*[3-7] *between the effective component (*$F_{EFF}$*, which will cause the rotation of the drive) and the total, i.e. resultant force produced by the active muscles (*$F_{Tot}$*). The other component (*$F_{INEFF}$*) is inefficient. An angle a of 0° (thus a total force vector oriented perpendicular to the crank arm) gives an effectiveness of 100%. Experienced cyclists usually have a high pedalling effectiveness*[4]*. In sprint running (right), the analogy we propose gives effectiveness as the ratio* $RF = F_{HZT} / F_{Tot.}$ *The analogy is not complete, since in running, the other component (*$F_{VTC}$*) is not totally useless: it is needed to keep the body up on the supporting ground and raise the CM sufficiently for the athlete to keep on accelerating forward.*

athlete) requires a GRF measuring device. Typically, in previous studies, force-plates were embedded into the supporting ground, or sprint instrumented treadmills were used. These systems have the following advantages and limits:

**Force plates** - Long used to measure GRF during sprint running[8-14], these show the importance of the horizontal force component and the corresponding impulse [9,10], and that of the forward incline of the resultant GRF vector[11,12]. However, their main drawback is that they only allow for measurements of a very limited number of steps (typically one to three). For instance, field sprint kinetics have been analysed for three steps or fewer during the starting blocks push-off and/or the first step of the sprint start[12,13,15], constant-speed runs[14,16], or, more recently, the acceleration phase (i.e. 16m[11]) and around top velocity (i.e. at 45m[8]). Finally, detailed kinetics of acceleration runs have been studied, and comparisons between different accelerations have been reported in comprehensive animal studies of turkeys[17] and dogs[18]. Although studying fast-running animals might give valuable information about acceleration capabilities, these studies are not directly and easily transferable to athletic performance.

**Instrumented treadmills** – These too have been used to study sprint running. However, apart from the obviously different running modality compared to sprinting over the ground, these devices only measure the vertical component of the GRF in top velocity sprinting[1,2,19-21]. Some treadmills (motorised) have the advantage of rolling up to typical 100m top velocities[1,2,20,22], but the subjects can not accelerate from a standing start all the way up to top speed: they typically have to “drop” themselves onto the rolling belt and try to run for about eight steps[20].

*Figure 2: The sprint instrumented treadmill*

*This treadmill and the brushless motor allow for typical accelerations from a standing start (for example first step on the left, eighth step on the right), up to maximum velocities of 8 to 9 $m.s^{-1}$ for the best sprinters tested. Once at top speed, the overall inclination of the body is vertical, similar to what is observed on the track.*

Very recently[23], we presented a sprint instrumented treadmill that has the particularity of 1) allowing for accelerations from a standing position (see Figure 2), 2) measuring both instantaneous horizontal and vertical components of the GRF at the sampling rate of 1000Hz, and 3) allowing subjects to accelerate "freely" and reach high running velocities. For full details about this novel and practically unique device (to our knowledge only one other laboratory in the world is equipped with one), see the methods section, and the references discussing its validity and advantages/limits[23], and the comparison of sprint performance between this treadmill and field conditions[24].

Until new data are presented and fully equipped tracks are made available to scientists and coaches, the sprint instrumented treadmill is the only device that allows us to quantify GRF in the three dimensions of space for all the steps of a typical sprint acceleration. Although highly innovative, this approach is of course subject to limitations, which will be discussed below.

Our aim in this project was to investigate the effectiveness of force application/orientation, and its relation to 100m sprint performance. Specifically, we wanted to know the relative importance of the capability to produce a high amount of total force (which we consider as a physical capability), and that of the ability to apply and orient this resultant force effectively (which we consider more as a technical ability) on 100m performance in the field. Furthermore, we wanted to test whether these two mechanical features of sprint acceleration were correlated, or whether they were disconnected, which would mean they represent two distinct abilities, and in turn two distinct tracks for training and development.

To this end, we undertook two protocols. First we studied a population of non-specialists and intermediate-level sprinters (Part 1). Then, we had the unique opportunity to collaborate with an elite group of athletes and further test our hypotheses in three national-level male sprinters, and in a world-class performer (Part 2).

## METHODS

### *Sprint instrumented treadmill*

The treadmill (ADAL3D-WR, Medical Developpement – HEF Tecmachine, Andrézieux-Bouthéon, France) is a highly rigid metal frame treadmill fixed to the ground through four piezoelectric force transducers (KI 9077b, Kistler, Winterthur, Switzerland) installed on a specially engineered concrete slab in our laboratory. It has been used for several years in "constant velocity" mode (e.g.)[25-30], and recently modified to enable a "constant motor torque" mode allowing athletes to perform sprints and accelerations from a still position. The basic principle is that once the default motor torque is set and compensates for the friction induced by subjects' weight onto the belt, any horizontal net force applied induces an acceleration of the belt, be it positive (force applied in the forward-to-backward direction) or negative in the opposite case (braking force).

It is described in full technical detail in MOZIN et al, 2010[23], and depicted in Figure 2. It allows very accurate simulation of the starting technique at the beginning of a sprint (subjects can lean forward in a still position as the treadmill belt is blocked, and then released at the exact moment of the start). It allows real "sprint starts" from a still position and for the athlete to lean forward with angles relative to the vertical that are close to data reported for standing sprint starts in the field. A comparison study[24] recently showed very similar shapes of speed-time curves obtained for athletes performing an entire 100m on the treadmill compared to field 100m speed-time curves obtained with a radar (Figure 4). Furthermore, this study showed that although acceleration and 100m performance were about 20-25% lower on the treadmill than in the field, the data were significantly and highly correlated between the two modalities. This allows sound inter-individual comparisons of acceleration and sprint biomechanics with this device, since the best sprinters on the track are also the best ones on the treadmill, and vice versa.

### Mechanical variables and data analysis

Mechanical data were sampled at 1000Hz throughout each sprint on the treadmill, 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 above 30N), which corresponds to the biomechanical/muscular specific event of one leg push. Instantaneous data of the vertical, horizontal and total GRF were averaged for each support phase ($F_{Vtc}$, $F_{Hzt}$ and $F_{Tot}$, respectively), expressed in body weight (BW) and used with the corresponding average belt speed ($V$ in $m.s^{-1}$) to compute net power in the horizontal direction ($P = F_{Hzt} \times V$, expressed in $W.kg^{-1}$). Finally, $F_{Vtc}$ was specifically averaged for the five steps around top velocity and reported as $F_{Vtc\text{-}Vmax}$.

### Ratio of forces and index of force application / orientation

For each step, $RF$ (in %) was calculated as the mean ratio of $F_{Hzt}$ to $F_{Tot}$ for one contact period. Further, we calculated an index of force application technique ($D_{RF}$) representing the decrement in $RF$ with increasing speed. Since with increasing speed the overall inclination of the body was expected to approach vertical, $D_{RF}$ 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 velocity (Figure 3). Therefore, the higher the $D_{RF}$ value (i.e. a flat $RF$-velocity relationship), the more $RF$ is maintained despite increasing velocity. Conversely, subjects with a low $D_{RF}$ (i.e. a steep $RF$-velocity relationship) were those who had the highest decreases in $RF$ with increasing velocity. To summarise 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 velocity during an acceleration run (or conversely, how they maintain $RF$ in order to produce high amounts of $F_{Hzt}$ during their acceleration).

### Field sprint performance

Performance over 100m on the track was measured by means of a radar Stalker ATS System™ (Radar Sales, Mineapolis, MN), which had been validated and used in previous human running experiments[31-33], to measure the forward velocity of the runner at a sampling rate of 35Hz. It was placed on a tripod 10m behind the subjects at a height of 1m (corresponding approximately to the height of subjects' CoM).

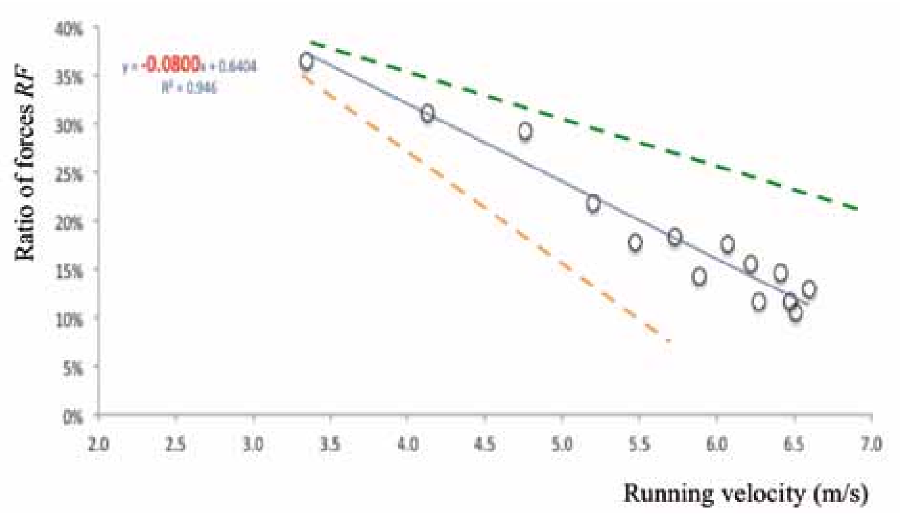


*Figure 3: Ratio of forces and Index of force orientation $D_{RF}$*

*This typical example (non-specialist, body mass = 68.1kg) of the RF-speed linear relationship obtained during a 6 sec sprint on the instrumented treadmill (from the second step and the step at top speed). Each point corresponds to values of RF and running speed averaged for one contact phase. The $D_{RF}$ index value for this subject is -0.080. The dashed lines would correspond to a better index for the green line (flatter relationship, i.e. more horizontal force produced as speed increases) and a worst index for the orange line (steeper relationship, i.e. the horizontal force drops faster as speed increases).*

From these measurements, speed-time curves were plotted (Figure 4), and maximal running velocity ($S_{max}$ in m/s) was obtained, as well as the 100m time ($t_{100}$ in sec) and the corresponding 100m mean velocity ($S_{100}$ in m/s). In addition, and in order to better analyse the performance, and compare the speed-time curves of subjects (**Part 2** only), radar speed-time curves were fitted by a bi-exponential function[24, 33, 34]:

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

$\tau 1$ and $\tau 2$ being respectively the time constant for acceleration and deceleration of this relationship, determined by iterative computerised solving.

### *Protocol PART 1: proof of concept in non-specialists and intermediate-level athletes*

Twelve male subjects (body mass (mean ± SD) 72.4 ± 8.6 kg; height 1.76 ± 0.08m; age 26.2 ± 3.6 yrs) 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 that include sprinting (e.g. soccer, basketball) in the six months preceding the study. Two subjects were national level long jump competitors (100m personal bests of 10.90 and 11.04 sec).

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 at the University of Saint-Etienne, and conducted according to the Declaration of Helsinki II.

The protocol consisted in performing one eight sec treadmill sprint and one 100m on a standard athletic Tartan™ track. The two sprints, which were performed in a randomised and counterbalanced order, were separated by 30 min of passive rest, and performed in similar ambient conditions. The subjects wore the same outfit and shoes in both efforts (no athletics spikes used). About one week prior to the testing session, the subjects undertook a familiarisation session during which they repeated treadmill sprints until becoming comfortable with the running technique required. For the testing session, the warm-up consisted of 5 min of 10 km.h$^{-1}$ running, followed by 5 min of sprint-specific muscular warm-up exercises, and three progressive six sec sprints separated by 2 min of passive rest. Subjects were then allowed ~5 min of free cool-down prior to the treadmill sprint. The warm-up preceding the 100m consisted in repeating the last part of the warm-up (from the three six sec sprints on).

On the treadmill, subjects were tethered by means of a leather weightlifting belt and thin stiff rope (0.6cm in diameter) rigidly anchored to the wall behind the subjects by a 0.4m vertical metal rail. When correctly attached, subjects were required to lean forward in a typical crouched sprint-start position (standardised for all subjects and close to that in the field) with their preferred foot forward. After a three sec 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.

### *Protocol PART 2: extension to national-level and world-class individuals*

Using the same protocol design as in **Part 1**, 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 yrs; body mass 72.6 ± 8.4kg; height 1.75 ± 0.08m) who were all physically active and had all practiced physical activities including sprinting (e.g. soccer, basketball) in the six months preceding the study, but were not sprint specialists. Three were French national-level sprinters (age (mean ± SD) 26.3 ± 2.1 yrs; body mass 77.5 ± 4.5kg; height 1.83 ± 0.05m). Their personal best times for 100m (last update 5 September 2011) ranged from 10.31 to 10.61 sec. The final subject, Christophe Lemaitre (CL) is a world-class sprinter (age: 21 yrs; body mass 81.0kg; height 1.91m). His official best performances were (last update 5 September 2011): 9.92 sec in the 100m and 19.80 sec in the 200m. Among his accomplishments are he was 2010 European Champion in 100m, 200m and 4x100m relay.

All subjects gave their informed consent to participate in this study after being informed about the procedures, which were approved by the local ethical committee [University of Saint-Etienne] and in agreement with the Declaration of Helsinki.

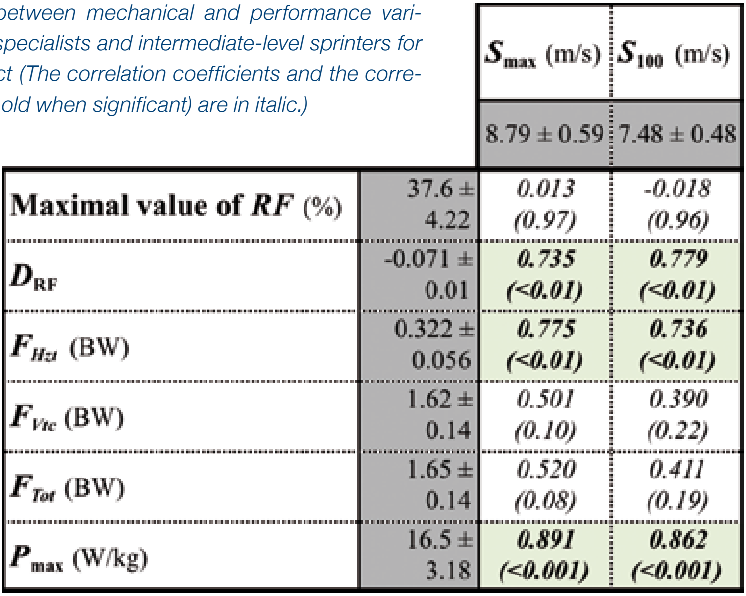
The non-specialist subjects performed the treadmill and field tests within a single testing session, as in the **Part 1** protocol. The world-class and national-level sprinters were tested on two distinct occasions: in mid-March and mid-April 2011 (treadmill and field performance measurements, respectively). This corresponded to the training period just preceding the beginning of their outdoor competitive season. 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.

### *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. Pearson's correlation was used between experimental variables measured on the treadmill and the field performance variables measured during the 100m. 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 since it was not a complete push-off) to the step at top velocity (Figure 3). The significance level was set at $P <$

0.05. The results of **Part 2** of the protocol are presented as a two-step comparison between three groups: the non-specialists (n = 9), the national-level sprinters (n = 3) and the world-class athlete (n = 1). The differences between the groups are presented as percent differences and number of SD.

*Table 1: Correlations between mechanical and performance variables obtained in non-specialists and intermediate-level sprinters for the Part 1 of this project (The correlation coefficients and the corresponding P values (in bold when significant) are in italic.)*



| | | $S_{max}$ (m/s) | $S_{100}$ (m/s) |
|---|---|---|---|
| | | 8.79 ± 0.59 | 7.48 ± 0.48 |
| **Maximal value of *RF* (%)** | 37.6 ± 4.22 | *0.013 (0.97)* | *-0.018 (0.96)* |
| $D_{RF}$ | -0.071 ± 0.01 | ***0.735 (<0.01)*** | ***0.779 (<0.01)*** |
| $F_{Hzt}$ (BW) | 0.322 ± 0.056 | ***0.775 (<0.01)*** | ***0.736 (<0.01)*** |
| $F_{Vtc}$ (BW) | 1.62 ± 0.14 | *0.501 (0.10)* | *0.390 (0.22)* |
| $F_{Tot}$ (BW) | 1.65 ± 0.14 | *0.520 (0.08)* | *0.411 (0.19)* |
| $P_{max}$ (W/kg) | 16.5 ± 3.18 | ***0.891 (<0.001)*** | ***0.862 (<0.001)*** |

## RESULTS

### *PART 1: proof of concept in non-specialists and intermediate-level athletes*

The values of the main mechanical and performance variables studied are listed in Table 1. On the track, subjects ran the 100m in 13.40 ± 0.85 sec (range: 11.90 - 15.01 sec), which corresponded to $S_{100}$ = 7.48 ± 0.48 m.s$^{-1}$, for a top velocity of 8.79 ± 0.59 m.s$^{-1}$ (range: 7.80 - 9.96 m.s$^{-1}$).

The index of force application technique, $D_{RF}$, was significantly and highly correlated to the two main 100m performance parameters: $S_{max}$ and $S_{100}$ ($P < 0.01$), as was the mean value of $F_{Hzt}$ over the acceleration ($P < 0.01$). Contrastingly, neither $F_{Vtc}$ nor $F_{Tot}$ averaged over the acceleration phase were correlated to these performance parameters. An exception to this result was when $F_{Vtc}$ was computed specifically at top speed on the treadmill: $F_{Vtc\text{-}Vmax}$ was significantly correlated (r = 0.612; P < 0.05) to the top speed reached on the track. Finally, the 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) or $D_{RF}$ (P = 0.25).

### *PART 2: extension to national-level and world-class individuals*

As expected, the field sprint performance (100m time) was more than two SD better for CL, the world-class sprinter (10.35 sec) than for the national-level sprinters (10.92 ± 0.20 sec), and much better than for the non-specialists (13.60 ± 0.70 sec). The performances of CL and national-level athletes corresponded to 96.1 and 95.6 ± 1.6% of their personal best times. Figure 4 illustrates the individual modelled speed-distance curves obtained during the 100m.

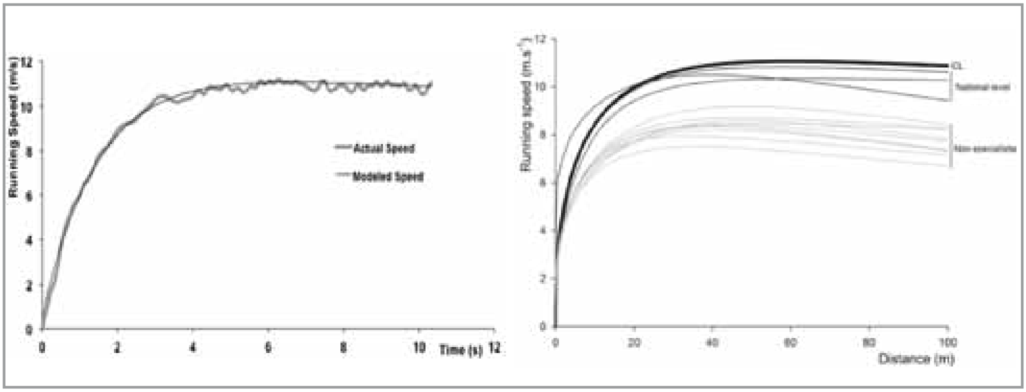


*Figure 4: 100m sprint performance analysis: actual and modeled speed-time curves*

***LEFT:*** *the speed-time curve was measured with a radar gun as shown in the pictures of the experimental setting (field 100m performance session). The typical data presented are those of the world-class athlete studied. During this trial, he ran the 100m in 10.35 sec, and reached a top speed of 11.2 m.s*$^{-1}$*, in 6.27 sec. The bi-exponential equation modeling his speed-time curve was:* $$S(t)=11.2\left[e^{((-t+6.27)/139))}-e^{(-t/1,46)}\right]$$

***RIGHT:*** *modeled speed-distance curves of the subjects tested in the Part 2 of the project: CL, the three national-level sprinters, and the nine non-specialists.*

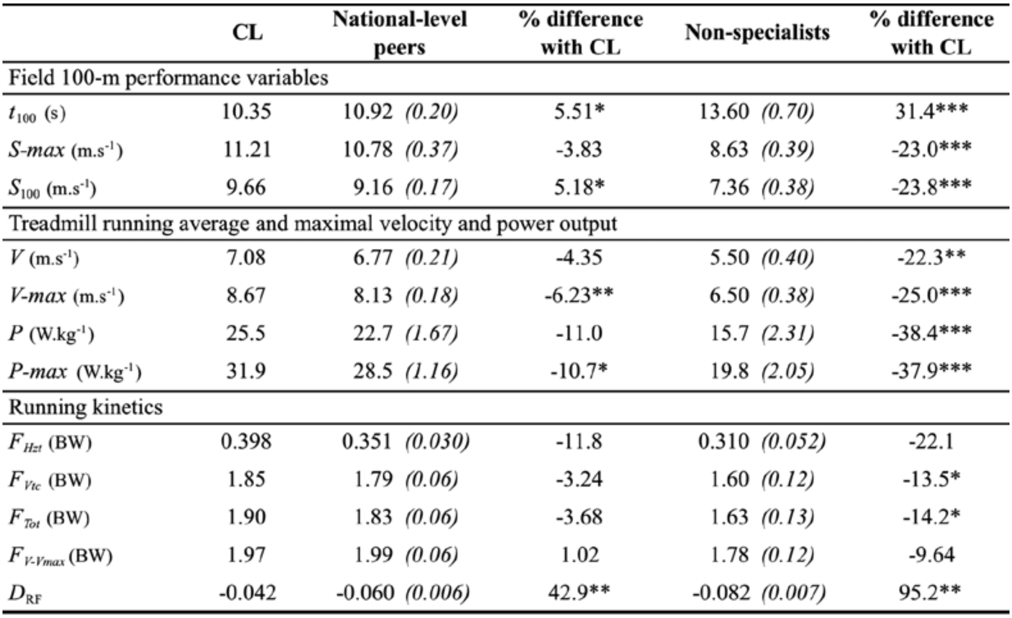
CL tested substantially different (more than two SD, Table 2) from his national-level counterparts for the maximal velocity and power output produced on the treadmill. Analysis of the GRF showed that he had remarkably higher values of $F_{Hzt}$ than the other individuals tested (Table 2), whereas his vertical and resultant force production per unit of BW were within the range of those of his national-level counterparts (yet much higher than for the non-specialists group). Furthermore, the ability of CL to produce high amounts of $F_{Hzt}$ versus $F_{Vtc}$ or $F_{Tot}$ was accompanied by the ability to maintain higher values of $F_{Hzt}$ with increasing velocity during acceleration on the treadmill. This is illustrated by the $D_{RF}$ index, which was 42.9% (3.21 SD) better than for national-level sprinters and 95.2% (3.47 SD) better than for non-specialists. Individual *RF*-velocity linear relationships (from which $D_{RF}$ is the slope) are detailed in Figure 5, in which one can observe the overall steeper *RF*-velocity relationship (i.e. faster decrease in *RF* with increasing velocity) as subjects' 100m performance level lowers.

Finally, in order to confirm the correlations obtained in the **Part 1** of this project, Table 3 shows that $D_{RF}$ index was significantly correlated to 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, $F_{Hzt}$ was significantly correlated to 100-m performance ($P$ < 0.01), whereas $F_{Vtc}$ was only correlated to $S_{max}$ ($P$ = 0.039), and not to $S_{100}$.

## DISCUSSION

It is clear from the results section that the two parts of this project essentially show similar results. Overall, they show that as subjects' performance level in the 100m increased, their ability to orient the resultant GRF generated by the lower limbs with a forward orientation, i.e. to produce higher amounts of horizontal net force at each step, also increased. This was not the case for the total amount of force produced, or for the vertical component of the GRF. Indeed, the force application technique,

*Table 2: Main field performance, running mechanics and power output variables for the world-class sprinter tested and the groups of national-level athletes (n = 3) and non-specialists (n = 9)*



| | CL | National-level peers | % difference with CL | Non-specialists | % difference with CL |
|---|---|---|---|---|---|
| **Field 100-m performance variables** | | | | | |
| $t_{100}$ (s) | 10.35 | 10.92 *(0.20)* | 5.51* | 13.60 *(0.70)* | 31.4*** |
| *S-max* ($m.s^{-1}$) | 11.21 | 10.78 *(0.37)* | -3.83 | 8.63 *(0.39)* | -23.0*** |
| $S_{100}$ ($m.s^{-1}$) | 9.66 | 9.16 *(0.17)* | 5.18* | 7.36 *(0.38)* | -23.8*** |
| **Treadmill running average and maximal velocity and power output** | | | | | |
| *V* ($m.s^{-1}$) | 7.08 | 6.77 *(0.21)* | -4.35 | 5.50 *(0.40)* | -22.3** |
| *V-max* ($m.s^{-1}$) | 8.67 | 8.13 *(0.18)* | -6.23** | 6.50 *(0.38)* | -25.0*** |
| *P* ($W.kg^{-1}$) | 25.5 | 22.7 *(1.67)* | -11.0 | 15.7 *(2.31)* | -38.4*** |
| *P-max* ($W.kg^{-1}$) | 31.9 | 28.5 *(1.16)* | -10.7* | 19.8 *(2.05)* | -37.9*** |
| **Running kinetics** | | | | | |
| $F_{Hzt}$ (BW) | 0.398 | 0.351 *(0.030)* | -11.8 | 0.310 *(0.052)* | -22.1 |
| $F_{Vtc}$ (BW) | 1.85 | 1.79 *(0.06)* | -3.24 | 1.60 *(0.12)* | -13.5* |
| $F_{Tot}$ (BW) | 1.90 | 1.83 *(0.06)* | -3.68 | 1.63 *(0.13)* | -14.2* |
| $F_{V\text{-}Vmax}$ (BW) | 1.97 | 1.99 *(0.06)* | 1.02 | 1.78 *(0.12)* | -9.64 |
| $D_{RF}$ | -0.042 | -0.060 *(0.006)* | 42.9** | -0.082 *(0.007)* | 95.2** |

Values are mean*(SD)*

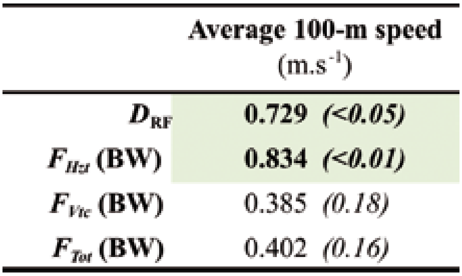
*: difference higher than 2SD

**: differences higher than 3SD

***: difference higher than 4SD

*Table 3: Correlations between mechanical variables of sprint kinetics measured during treadmill sprints (rows) and 100m performance (column).*
*Obtained by pooling the data of the 13 subjects of the Part 2 of this project.*

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



| | Average 100-m speed ($m.s^{-1}$) |
|---|---|
| $D_{RF}$ | **0.729 *(<0.05)*** |
| $F_{Hzt}$ (BW) | **0.834 *(<0.01)*** |
| $F_{Vtc}$ (BW) | 0.385 *(0.18)* |
| $F_{Tot}$ (BW) | 0.402 *(0.16)* |

and more precisely the ability to limit the decrease in *RF* during accelerated runs on a sprint treadmill despite the increasing velocity, was highly correlated (*P* < 0.05) to field 100m performance (top and mean velocities).

Thus, the way sprinters apply force onto the ground (technical ability) seems to be more important to sprint performance than the amount of total force they are able to produce (physical capability). In addition, these two mechanical features of the acceleration kinetics were not correlated, which means they correspond to distinct skills.

To our knowledge, this is one of the very few studies to specifically report experimental data directly and specifically obtained in a group of subjects ranging from non-specialists to national-level sprinters, and to a world-class athlete. Since pioneering works about human sprint performance published in the late 1920s[35,36] involving very fast runners (estimated 100m time of ~10.8 sec for subject H.A.R., probably the 1928 Olympian Henry Argue Russel) reported by FURUSAWA et al. [36,37], many studies have involved high-level athletes (e.g.[8,16,38]) but not truly world-class performers.

### *PART 1: proof of concept in non-specialists and intermediate-level athletes*

The comparison of *RF* and $D_{RF}$ data with previous studies is limited since 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 (since *RF* equals the sine of this angle). For instance, at the first step of a maximal acceleration from a standing start, KUGLER & JANSHEN[11] reported a forward orientation of the maximal GRF 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 (Figure 5). Furthermore, 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[12]), the calculated net horizontal and vertical forces were ~325 and 288N, respectively. This corresponds to an estimated total force of ~434N, and a *RF* of ~74.9%. Our maximal values of *RF* are well in line with those of KUGLER & JANSHEN[11], but far below those of MERO[12]. This could be explained by the fact that, contrary to our study and that of KUGLER & JANSHEN[11], the subjects did not make the start from a crouched position. Instead, the 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*.

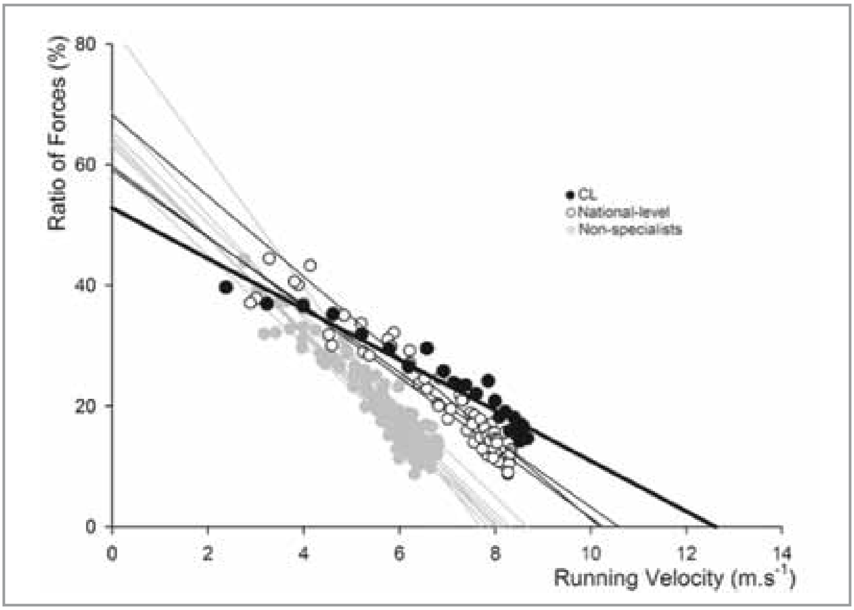


*Figure 5: RF-velocity linear relationships during the acceleration on the instrumented treadmill*

*Individual RF-velocity linear relationships during the acceleration phase of the treadmill sprint for the three populations compared in the Part 2 of the project. Each point represents average values of ratio of forces and velocity for one contact phase. The two dashed red lines show that, at a given running velocity (for instance 7 and 8 $m.s^{-1}$) on the treadmill, the best athletes are able to produce a higher RF at each step: national-level athletes more than non-specialists (the latter reached top running velocities around 7 m/s on the treadmill), and CL more than his national-level peers.*

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. Therefore, we think that $D_{RF}$ (the slope of the *RF*-speed relationship) is a good index of the technical ability of runners to apply force effectively onto the ground over the entire acceleration phase: its value depends on the ability to orient total force at each step, during the entire acceleration phase.

Contrary to $F_{Vtc}$ (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 velocity on the treadmill ($F_{Vtc\text{-}Vmax}$) was significantly linked to track $S_{max}$ ($P < 0.05$). This confirms the results of WEYLAND et al.[2], who showed a similar significant relationship between $F_{Vtc\text{-}Vmax}$ and $S_{max}$ ($r^2 = 0.39$; $P = 0.02$; n = 33 compared to $r^2 = 0.38$; $P = 0.03$; n = 12 in the present study), yet for a much wider range of top velocities (6.2 to 11.1 $m.s^{-1}$ compared to 7.80 to 9.96 $m.s^{-1}$). Our results also confirm those of WEYLAND et al.[2] that applying a high amount of vertical force per unit BW at the moment top velocity 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 acceleration phase of a sprint. Indeed, during the acceleration phase, our results show that $F_{Hzt}$ is a key variable, but not $F_{Vtc}$.

The 100m has often been described as a three-component race: acceleration phase, approximately constant maximal velocity phase and deceleration phase[34,39,40]. Our results support the fact that net horizontal force and power, partly influenced by the 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.

These results were obtained in low-level sprinters and in non-specialists. The following Part is aimed at verifying their consistency in a much higher performance-level population.

### *PART 2: extension to national-level and world-class individuals*

The main results of the present two-step comparison between a world-class sprinter, national-level counterparts and non-specialists allowed us to compare a spectrum of biomechanical parameters related to 100m sprint performance.

First, the 100m field performance test confirmed what was expected from subjects' personal best times: with all sprinters performing close to 96% of their best times at the moment of the study, CL ran about 5.5% (2.95 SD) faster than the other sprinters on average (Table 2). During the treadmill sprint tests, CL produced higher mechanical power normalised to body mass in the horizontal direction, and especially, his $P_{max}$ was ~8 % higher than for the other sprinters, and ~36 % (5.90 SD) higher than that of non-specialists (Table 2). Furthermore, this higher mechanical power was due to both a higher velocity (both *V* and $V_{max}$ values) and a higher $F_{Hzt}$ (Table 2).

When pooling the data of **Part 2** of this project, we confirmed the significant and clear correlation between 100m performance and average or maximal mechanical power normalised to body mass in the horizontal direction ($P < 0.01$), which was expected from previous findings (e.g.[41-44]), but the present study added to these data that mechanical power was this time measured during the specific sprinting exercise[23], contrary to the previously cited protocols in which power output was assessed during vertical, horizontal or incline push-offs, or in sprint cycling.

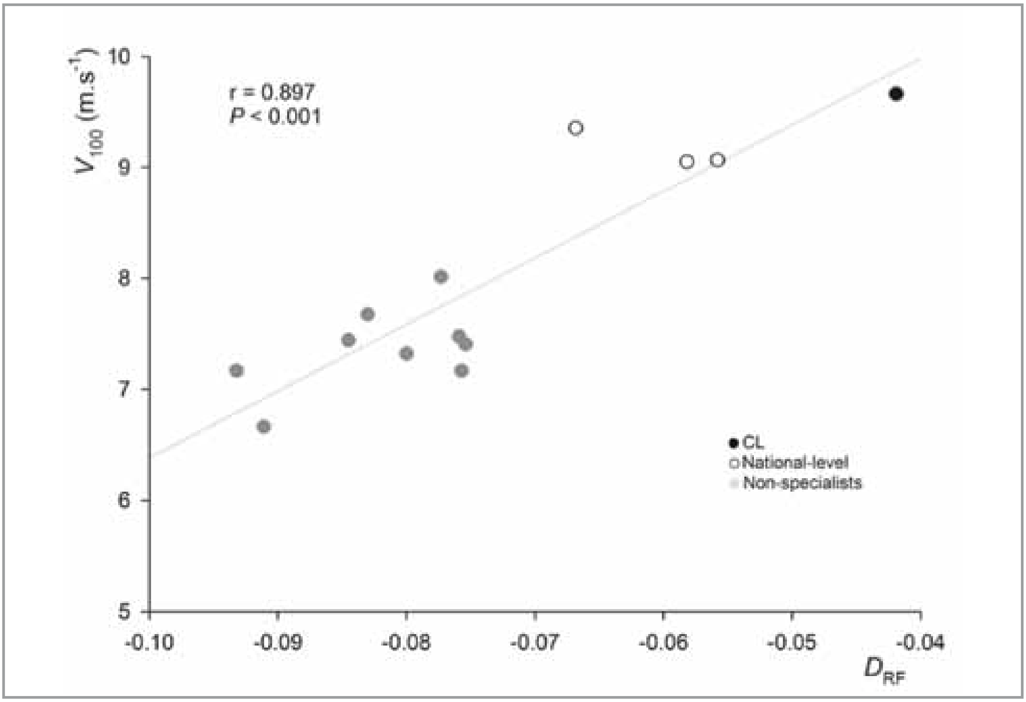


*Figure 6: Correlation between the index of force application $D_{RF}$ measured during treadmill sprints and the average running speed in the 100m*

*This correlation obtained with the data of the Part 2 of this project confirms the data obtained in the Part 1. The data of national-level sprinters and those of CL extend our initial hypothesis that the way the resultant force is applied onto the ground during the acceleration on the treadmill is a key determinant of sprint 100m performance.*

We also observed, as in **Part 1** of this project, a high and significant correlation between sprint performance and the ability to produce net horizontal force per unit of BW $F_{Hzt}$ (Table 3). Given the much poorer correlation obtained with resultant force production $F_{Tot}$ (only correlated to $S_{max}$, and not to $S_{100}$), the better ability to produce and apply high $F_{Hzt}$ 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 much higher for CL, and significantly correlated to the main performance parameters tested (Table 3). The present results almost exactly match those reported in **Part 1** of this project: $F_{Tot}$ was not significantly related to $S_{100}$ when pooling the data of all the subjects tested ($P$ = 0.16), whereas $D_{RF}$ was ($P$ = 0.012). Furthermore, the only performance parameter significantly related to the vertical or resultant force production was maximum velocity (Table 3).

The specific data of CL presented in Table 2 show that his $F_{Hzt}$ and $D_{RF}$ are indeed far better than that of his national level peers, yet his $F_{Tot}$ value is within the range of that of his peers. To summarise, on average during a six sec sprint on the treadmill, he was able to produce the same amount of $F_{Tot}$ as national-level athletes (or even some of the non-specialists), but his outstanding ability to orient the resultant force forward led him to produce a $F_{Hzt}$ that was 12% higher than his national-level counterparts (one of them is a member of the national 4x100m relay team) and 22% higher than for non-specialists.

### *Limits of the approach*

One limit of the present study is that sprinting mechanics were investigated during runs performed on an instrumented treadmill, and not over the ground. Despite the fact that to date continuously measuring running kinematics and kinetics over an entire sprint acceleration phase is not possible in other conditions than those presented here, one may contest the external validity of using an instrumented treadmill to study human sprint running mechanics. The literature is not clear as to the fundamental differences between these two conditions. For instance, some studies[45,46] showed biomechanical differences between field and treadmill sprint running, whereas another[47] recently concluded that sprinting on a treadmill is similar to over the ground for the majority of the kinematic variables they studied, and specified that a motorised treadmill was necessary to reach a similarity between the two conditions of measurements, which was the case in the present study.

That said, 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 maximal running velocity on the treadmill, we can reasonably hypothesise that the inter-individual differences observed in physical and technical capabilities did not fundamentally differ between treadmill and track conditions. Data recently published and obtained with the instrumented treadmill used in the present study showed that the performance parameters studied were significantly correlated between field and treadmill sprint conditions[24]. Therefore, we think that despite the lower performance observed on the treadmill, the comparison between subjects was not fundamentally challenged. Finally, we think that the advantage and novelty of being able to continuously measure GRF and *RF* and compute $D_{\mathrm{RF}}$ over the entire acceleration phase of a maximal effort sprint outweighs the issue of lower sprint performance.

In line with this, another limit of the present study is that we did not observe *RF* values reaching zero as subjects reached their top speed on the treadmill (Figure 3 and 5), which, theoretically, should have been the case. This is due to the fact that 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-velocity. Indeed, we estimated the net horizontal force production during the field 100m from speed-time curves, forward acceleration as a function of time and basic laws of dynamics[24]. These data clearly support the hypothesis that the difference 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 $F_{Hzt}$ produced.

This limit may not fundamentally challenge the proposed calculation of $D_{\mathrm{RF}}$. As may be observed in Figure 5, and as mentioned above, the right parts of *RF*-speed linear regressions do not reach null values of *RF* (*y*-axis) or maximal velocities similar to those observed in the field (*x*-axis). Given that 1) $D_{\mathrm{RF}}$ is computed as the slope of this linear relationship and 2) this linearity is significant and clear for all subjects for the range of *RF* and velocities tested on the treadmill (i.e. up to about 6 to 8 $\mathrm{m.s^{-1}}$ 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), $D_{\mathrm{RF}}$ values would have been very close to those reported.

To support this assumption, we compared theoretical treadmill top velocity values (*x*-axis intercept obtained by extrapolation of the linear *RF*-speed relationship) to field $S_{\max}$ for each individual. The values were very close (8.53 ± 0.84 $\mathrm{m.s^{-1}}$ on the treadmill compared to 8.79 ± 0.59 $\mathrm{m.s^{-1}}$) and highly correlated ($r = 0.899$; $P < 0.001$). We recently collected GRF data during 40m sprints on a track (data and publications in process) in elite athletes, and the computations of *RF* and $D_{RF}$ basically show that i) a linearity in the *RF* -speed is also observed, ii) at top speed, an *RF* value of 0% (which is mechanically logical by definition) is reached, and iii) data are remarkably similar between treadmill and track measurements.

Finally, although measured and available in the other published papers linked to this project, we did not focus here on sprint kinematics and stride temporal parameters, for two main reasons. First, we thought these data were much less innovative than the force and force application data presented here. Second, these sprint kinematics and stride temporal characteristics are well detailed in the literature (e.g. SALO et al.[48]), and usually measured during sprints over the ground and often during competitions. Thus, we thought the treadmill measurements less qualitative and close to sprinting reality, and overall we thought these data less relevant to the development of athletics than the other data detailed in this project.

## Conclusion

This project including national- and world-class level athletes as well as non-specialists provided qualitative information towards a better understanding of the biomechanical correlates of sprint running performance. The main result of the present study is that a higher level of acceleration and overall performance in the 100m are mainly associated with a higher ability to apply the resultant GRF vector with a forward orientation over the acceleration. In contrast, resultant GRF magnitude was not related to acceleration and overall 100m performance, but it was to top running velocity. Specifically, the world-class athlete tested did not show an outstanding total force production capability but he was able to produce much more horizontal force than the other subjects (national-level sprinters and non-specialists), especially at high running velocities.

These results raise the question of a better balance in a sprinter's strength-training regimen between the need for producing total force with the lower limbs, on the one hand, and efficiently transmitting it and orienting it forward during the support phase, on the other. We can reasonably recommend that the strength and conditioning training should be oriented towards improving the ability to limit the loss of *RF* during the acceleration phase of the race. To do so, our thinking is that consideration should be given to two possible paths of development: 1) focusing on hip extensor muscles (mainly the gluteus and hamstrings) for their role in backward propulsion of the lower limb, especially as the velocity increases and the overall body position "verticalises" and 2) the ankle stabiliser muscles, for their contribution to transmitting the force generated into the ground. The importance of the latter's work, especially at high velocity, might currently be underestimated compared to the maximal strength of the knee extensors or plantar flexors.

Further studies should focus on the necessity, effectiveness and practical feasibility of training programmes/exercises that could develop the key variables of sprint performance put forward in this project. Specifically, 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. Since 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.

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## REFERENCES

1. WEYAND, P.G.; SANDELL, R.F.; PRIME, D.N.L. & BUNDLE, M.W. (2010) The biological limits to running speed are imposed from the ground up. *Journal of Applied Physiology,* 108 (4), 950-961.

2. WEYAND, P.G.; STERNLIGHT, D.B.; BELLIZZI, M.J. & WRIGHT, S. (2000) Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *Journal of Applied Physiology,* 89 (5), 1991-1999.

3. DAVIS, R.R. & HULL, M.L. (1981). Measurement of pedal loading in bicycling: II. Analysis and results. *Journal of Biomechanics,* 14 (12), 857-872.

4. DOREL, S.; COUTURIER, A.; LACOUR, J.R.; VANDEWALE, H.; HAUTIER, C. & HUG, F. (2010). Force-velocity relationship in cycling revisited: benefit of two-dimensional pedal forces analysis. *Medicine and Science in Sports and Exercise,* 42 (6), 1174-1183.

5. ERICSON, M.O. & NISELL, R. (1988). Efficiency of pedal forces during ergometer cycling. *International Journal of Sports Medicine,* 9 (2), 118-122.

6. PATTERSON, R.P. & MORENO, M.I. (1990). Bicycle pedalling forces as a function of pedalling rate and power output. *Medicine and Science in Sports and Exercise,* 22 (4), 512-516.

7. SANDERSON, D.J. (1991). The influence of cadence and power output on the biomechanics of force application during steady rate cycling in cometitive and recreational cyclists. J*ournal of Sports Science,* 9, 191-203.

8. BEZODIS, I.N.; KERWIN, D.G. & SALO, A.I. (2008). Lower-limb mechanics during the support phase of maximum-velocity sprint running. *Medicine and Science in Sports and Exercise,* 40 (4), 707-715.

9. HUNTER, J.P.; MARSHALL, R.N. & MCNAIR, P.J. (2005). Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *Journal of Applied Biomechanics,* 21 (1), 31-43.

10. KAWAMORI, N.; NOSAKA, K. & NEWTON, R.U. (2013). Relationships between ground reaction impulse and sprint acceleration performance in team-sport athletes. *Journal of Strength and Conditioning Research,* 27 (3), 568-573.

11. KUGLER, F. & JANSHEN, L. (2010). Body position determines propulsive forces in accelerated running. *Journal of Biomechanics,* 43 (2), 343-348.

12. MERO, A. (1988). Force-time characteristics and running velocity of male sprinters during the acceleration phase of sprinting. *Research Quarterly in Exercise and Sport* 59 (2): 94-98.

13. MERO, A.; LUHTANEN, P. & KOMI, P.V. (1983). A biomechanical study of the sprint start. *Scandinavian Journal of Sports Science,* 5 (1), 20-28.

14. NUMMELA, A.; KERANEN, T. & MIKKELSSON, L.O. (2007). Factors related to top running speed and economy. *International Journal of Sports Medicine,* 28 (8), 655-661.

15. CHARALAMBOUS, L.; IRWIN, G.; BEZODIS, I.N. & KERWIN, D. (2012). Lower limb joint kinetics and ankle joint stiffness in the sprint start push-off. *Journal of Sports Science,* 30 (1), 1-9.

16. MERO, A. & KOMI, P.V. (1986). Force-, EMG-, and elasticity-velocity relationships at submaximal, maximal and supramaximal running speeds in sprinters. *European Journal of Applied Physiology,* 55 (5), 553-561.

17. ROBERTS, T.J. & SCALES, J.A. (2002). Mechanical power output during running accelerations in wild turkeys. *Journal of Experimental Biology,* 205, 1485-1494.

18. WALTER, R.M.; CARRIER, D.R. (2009). Rapid acceleration in dogs: ground forces and body posture dynamics. *Journal of Experimental Biology,* 212 (12), 1930-1939.

19. BUNDLE, M.W.; ERNST, C.L.; BELLIZZI, M.J.; WRIGHT, S. & WEYAND, P.G. (2006) A metabolic basis for impared force production and neuromuscular compensation during sprint cycling. *American Journal of Physiology - Regulatory, Integrative and Comparative Physiology,* 291, 1457-1464.

20. WEYAND, P.G.; BUNDLE, M.W.; MCGOWAN, C.P.; GRABOWSKI, A.; BROWN, M.B.; KRAM, R. & HERR, H. (2009). The fastest runner on artificial legs: different limbs, similar function? *Journal of Applied Physiology,* 107 (3), 903-911.

21. WEYAND, P.G.; LIN, J.E. & BUNDLE, M.W. (2006). Sprint performance-duration relationships are set by the fractional duration of external force application. A*merican Journal of Physiology - Regulatory, Integrative and Comparative Physiology,* 290 (3), 758-765.

22. BOWTELL, M.V.; TAN, H. & WILSON, A.M. (2009). The consistency of maximum running speed measurements in humans using a feedback-controlled treadmill, and a comparison with maximum attainable speed during overground locomotion. *Journal of Biomechanics,* 42 (15), 2569-2574.

23. MORIN, J.B.; SAMOZINO, P.; BONNEFOY, R.; EDOUARD, P. & BELLI, A. (2010). Direct measurement of power during one single sprint on treadmill. *Journal of Biomechanics,* 43, 1970-1975.

24. MORIN, J.B.; SEVE, P. (2011) Sprint running performance: comparison between treadmill and field conditions. *European Journal of Applied Physiology,* 111 (8), 1695-1703.

25. AVOGADRO, P.; DOLENEC, A. & BELLI, A. (2003). Changes in mechanical work during severe exhausting running. *European Journal of Applied Physiology,* 90 (1-2), 165-170.

26. DIVERT, C.; MORNIEUX, G.; BAUR, H.; MAYER, F. & BELLI, A. (2005). Mechanical comparison of barefoot and shod running. *International Journal of Sports Medicine*, 26 (7), 593-598.

27. DIVERT, C.; MORNIEUX, G.; FREYCHAT, P.; BALY, L.; MAYER, F. & BELLI, A. (2008). Barefoot-shod running differences: shoe or mass effect? I*nternational Journal of Sports Medicine*, 29 (6), 512-518.

28. MILLET, G.Y.; MORIN, J.B.; DEGACHE, F.; EDOUARD, P.; FÉASSON, L.; VERNEY, J: & OULLION, R. (2009). Running from Paris to Beijing: biomechanical and physiological consequences. *European Journal of Applied Physiology*, 107, 731-738.

29. MORIN, J.B.; DALLEAU, G.; KYROLAINEN, H.; JEANNIN, T. & BELLI, A. (2005). A simple method for measuring stiffness during running. *Journal of Applied Biomechanics*, 21 (2), 167-180.

30. MORIN, J.B.; SAMOZINO, P.; ZAMEZIATI, K. & BELLI, A. (2007). Effects of altered stride frequency and contact time on leg-spring behavior in human running. *Journal of Biomechanics*, 40 : 3341-3348.

31. CHELLY, S.M. & DENIS, C. (2001). Leg power and hopping stiffness: relationship with sprint running performance. *Medicine and Science in Sports and Exercise*, 33 (2), 326-333.

32. DI PRAMPERO, P.E.; FUSI, S.; SEPULCRI, L.; MORIN, J.B.; BELLI, A. & ANTONUTTO, G. (2005). Sprint running: a new energetic approach. *Journal of Experimental Biology*, 208, 2809-2816.

33. MORIN, J.B.; JEANNIN, T.; CHEVALLIER, B. & BELLI, A. (2006). Spring-mass model characteristics during sprint running: correlation with performance and fatigue-induced changes. *International Journal of Sports Medicine*, 27 (2), 158-165.

34. VOLKOV, N.I. & LAPIN, V.I. (1979). Analysis of the velocity curve in sprint running. *Medicine and Science in Sports*, 11 (4), 332-337.

35. BEST, C.H. & PARTRIDGE, R.C. (1928). The equation of motion of a runner, exerting a maximal effort. *Proceedings of the Royal Society - Biology*, 103, 218-225.

36. FURUSAWA, K.; HILL, A.V. & PARKINSON, J.L. (1927). The energy used in "sprint" running. *Proceedings of the Royal Society - Biology*, 102, 43-49.

37. FURUSAWA, K.; HILL, A.V. & PARKINSON, J.L. (1927) The dynamics of "sprint" running. *Proceedings of the Royal Society - Biology* 102, 29-42.

38. KARAMANIDIS, K.; ALBRACHT, K.; BRAUNSTEIN, B.; CATALA, M.M.; GOLDMANN, J.P. & BRÜGGEMANN, G.P. (2011). Lower leg musculoskeletal geometry and sprint performance. *Gait and Posture*, 34 (1), 138-141.

39. DELECLUSE, C.; VAN COPPENOLLE, H.; WILLEMS, E.; DIELS, R.; GORIS, M.; VAN LEEMPUTTE, M. & VUYLSTEKE. M (1995). Analysis of 100 meter sprint performance as a multidimensional skill. *Journal of Human Movement Studies*, 28, 87-101.

40. MERO, A.; KOMI, P.V. & GREGOR, R.J. (1992). Biomechanics of sprint running. A review. *Sports Medicine,* 13 (6), 376-392.

41. CRONIN, J. & HANSEN, K.T. (2005). Strength and power predictors of sports speed. J*ournal of Strength and Conditioning Research,* 19 (2), 349-357.

42. CRONIN, J. & SLEIVERT, G. (2005). Challenges in understanding the influence of maximal power training on improving athletic performance. *Sports Medicine,* 35 (3), 213-234.

43. HARRIS, N.K.; CRONIN, J.B.; HOPKINS, W.G. & HANSEN, K.T. (2008). Relationship between sprint times and the strength/power outputs of a machine squat jump. J*ournal of Strength and Conditioning Research,* 22 (3), 691-698.

44. SLEIVERT, G. & TAINGAHUE, M. (2004). The relationship between maximal jump-squat power and sprint acceleration in athletes. *European Journal of Applied Physiology,* 91 (1), 46-52.

45. FRISHBERG, B.A. (1983.) An analysis of overground and treadmill sprinting. *Medicine and Science in Sports and Exercise,* 15 (6), 478-485.

46. KIVI, D.M.; MARAJ, B.K. & GERVAIS, P. (2002). A kinematic analysis of high-speed treadmill sprinting over a range of velocities. *Medicine and Science in Sports and Exercise,* 34 (4), 662-666.

47. MCKENNA, M.J. & RICHES, P.E. (2007). A comparison of sprinting kinematics on two types of treadmill and overground. *Scandinavian Journal of Medicine and Science in Sports,* 17, 649-655.

48. SALO, A.I; BEZODIS, I.N.; BATTERHAM, A.M. & KERWIN, D.G. (2011). Elite Sprinting: Are Athletes Individually Step Frequency or Step Length Reliant? *Medicine and Science in Sports and Exercise,* 43 (6), 1055-1062.