New insights into sprint biomechanics and determinants of elite 100m performance

DESCRIPTION OF THE PROJECT

Introduction

Short sprint performance (100-m and 50 or 60-m) strongly relies on athletes’ capability to accelerate their mass and generate high amounts of running speed in the forward direction of motion. To do so, their neuromuscular system, and especially that of their trunk and lower limbs generate force, and this force is in turn applied onto the supporting ground during the support phase of the running step cycle, i.e. during the short (~100 ms or less in top sprinters) contact between the foot (and mostly the forefoot) and the ground.

While the performance during the phase of constant top running speed and the ability to run at high top speed have been clearly related to the ability to generate high amounts of ground reaction force (GRF) in the vertical direction, and limited by contact duration (Weyand et al. 2010; Weyand et al. 2000), much less is known about the determinants of the acceleration phase. The latter phase represents about 60 to 70% of the entire 100-m in top-level athletes (DLV 2009). Therefore, this project centers on the mechanical determinants of acceleration and 100-m performance, with a very specific focus on the magnitude and orientation of the ground reaction forces.

Coaching practice has long considered the capability of force production as an inherent feature of acceleration and sprint capability. How much force and impulse athletes are able to produce and how hard they can “push the ground” and “push with a forward incline” in the starting-blocks phase, during the first, second stance, and overall during the entire acceleration phase is without doubt a key variable. Most of the sprint specific training is in fact dedicated to develop or maintain this capability. Furthermore, from a purely biomechanical standpoint, moving the center of mass (CoM) (and in turn the entire body) in the forward direction requires propelling through the application of forces onto the supporting ground, the impulse of which will determine the amount of change in the velocity of the center of mass (Newton’s law of motion). Form this basic principle, step after step during the acceleration phase, athletes have in theory two possibilities to generate high amounts of forward acceleration and running speed: apply high amounts of resultant (i.e. total) GRF, and/or orient this resultant force with a forward incline. Indeed, the more forward the orientation of the resultant force applied, the higher the forward (horizontal) component of the GRF and the lower the vertical one (Figure 1).

Mathematically, as explained in Figure 1, the angle of the resultant GRF vector determines, for a given amount of GRF, the values of the horizontal and vertical components of the resultant GRF. The two latter will cause the forward horizontal and vertical accelerations of the CoM, respectively.

Although a certain amount of vertical GRF is needed to simply stand and make the running motion possible, the intensity of the forward acceleration will mainly depend on the amount of horizontal net GRF applied onto the ground at each step. As previously proposed in pedaling mechanics (Davis and Hull 1981; Dorel et al. 2010; Ericson and Nisell 1988; Patterson and Moreno 1990; Sanderson 1991), 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 is produced during each pedal rotation. Thus, we used the analogy with the well-known mechanical effectiveness in pedaling mechanics to propose the effectiveness of force application / orientation in sprint running.

Basically, as shown in Figure 1, we define the ratio of force (RF) as the ratio of the contact-averaged horizontal force $F_{H\text{zt}}$ to the corresponding resultant GRF ($F_{\text{Tot}}$). Thus, theoretically, for the same $F_{\text{Tot}}$ 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 $F_{H\text{zt}}$.
We therefore hypothesized that RF could objectively represent athletes’ force application technique, and that it could also be independent from the amount of total force applied, i.e., their physical capabilities.

However, the main limitation faced here was that measuring RF at each step of an acceleration phase (typically 40 to 60 or even 70 m depending on the level of the athlete) requires a GRF measuring device. Typically, in previous studies, force-plates were embedded into the supporting ground, or sprint instrumented treadmill were used.

Here are the main advantages / limits and data put forward with these two kinds of systems:

- **Force plates:**
  They have long been used to measure GRF during sprint running (e.g. Bezodis et al. 2008; Hunter et al. 2005; Kawamori et al. 2012; Kugler and Janshen 2010; Mero 1988; Mero et al. 1983; Nummela et al. 2007), show the importance of the horizontal force component and the corresponding impulse (Hunter et al. 2005; Kawamori et al. 2012), and that of the forward incline of the resultant GRF vector (Kugler and Janshen 2010; Mero 1988). 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 analyzed for three steps or fewer during the starting blocks push-off and/or the first step of the sprint (Charalambous et al. 2012; Mero 1988; Mero et al. 1983), constant-speed runs (Mero and Komi 1986; Nummela et al. 2007), or, more recently, the acceleration phase (i.e. 16 m Kugler and Janshen 2010) and around top speed (i.e. 45 m Bezodis et al. 2008). Finally, detailed kinetics of acceleration runs have been studied, and comparisons between different accelerations have been reported in comprehensive animal studies of turkeys (Roberts and Scales 2002) and dogs (Walter and Carrier 2009). Although studying fast-running animals might give precious information about acceleration capabilities, these studies are not directly and easily transferable to athletic performance.

- **Instrumented treadmills:**
  On the other hand, sprint instrumented treadmills have been used to study sprint running. However, apart from the obviously different running modality compared to overground sprinting, these devices only measured the vertical component of the GRF at top speeds during sprints (Bundle et al. 2006; Weyand et al. 2009; Weyand et al. 2006; Weyand et al. 2010; Weyand et al. 2000). Some of them (motorized) have the advantage of rolling up to typical 100-m top speeds (Bowtell et al. 2009; Weyand et al. 2009; Weyand et al. 2010; Weyand et al. 2000), but on the other hand, subjects can not accelerate from a standing start until top speed: they typically have to “drop” themselves onto the rolling belt and try and run for about 8 steps (e.g. Weyand et al. 2009).

Very recently (Morin et al. 2010), we presented a sprint instrumented treadmill that has the particularity of (i) allowing for accelerations from a standing still position (see Figure 2), (ii) measuring both instantaneous horizontal and vertical components of the GRF at the sampling rate of 1000 Hz, and (iii) allowing subjects to accelerate “freely” and reach high running speeds. For full details about this novel and unique device (to date our laboratory is the only one equipped with this device), see the methods section, and the references discussing its validity and advantages / limits (Morin et al. 2010), and the comparison of sprint performance between this treadmill and field conditions (Morin and Sève 2011). **This device was the focus of our 2010 entry to the EAA Innovation award, category “Technology”** (Morin et al. 2010, EAA entry, Honorable mention).

Until new data are presented and fully equipped tracks are made available to scientists and athletics coaches, the sprint instrumented treadmill mentioned here is the only device allowing 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 at the end of this entry.
Aims of the study

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

To this aim, we undertook two distinct protocols, which correspond to the two recently published studies accompanying this entry. 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 individual (Part 2).

Particular relevance to the development of athletics

Two features of the present project support this relevance:

- **Innovative approach and technology:**
  The device used and the concept of effectiveness of force application have been proposed and tested since only 2010. Although obviously open to discussion, the data put forward and shown in the present project will surely generate / catalyze discussions in the scientific and training community, and more importantly between these two communities. We are convinced it will at least generate other scientific data / publication, and at best help coaches and athletes better orient their daily work.

- **High level population:**
  The second part of the project aimed at extending the hypotheses tested in the first part to a population of highly skilled specialists. As detailed in the methods, we had the unique opportunity to collaborate with an elite group in which three national-level male sprinters and a world-class individual participated to the laboratory and field experiment. The latter (French sprinter Christophe Lemaitre, identified as CL in this entry) currently has personal best times of 9.92 s and 19.80 s on 100-m and 200-m, respectively, has been the 2010 European Champion on 100-m, 200-m and 4x100-m relay, and has been named 2010 European Athlete of the year by the EAA.

Beyond the “case-study” aspect of this part of the project, we are convinced that the presentation and discussion of such an exceptional individual’s data give strength and relevance to the approach, in relation to the current and future development of athletics.

Methods

**Sprint instrumented treadmill**

The treadmill (ADAL3D-WR, MedicalDeveloppement – 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), and installed on a specially engineered concrete slab in our Laboratory. It has been used for several years in “constant velocity” mode (e.g. Avogadro et al. 2003; Divert et al. 2005; Divert et al. 2008; Millet et al. 2009; Morin et al. 2005; Morin et al. 2007), and recently modified to enable a “constant motor torque” mode allowing 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 details in (Morin et al. 2010; Morin et al. 2010, EAA entry), and depicted in Figure 2. It allows to reproduce very accurately the starting technique at the beginning of a sprint (subjects can lean forward in 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 to lean forward with angles relative to the vertical that are close to data reported in field standing sprint starts. A comparison study (Morin and Sève 2011) recently showed very similar shapes of speed-time curves obtained when performing an entire 100-m on the treadmill compared to field 100-m speed-time curves obtained with a radar (Figure 4). Furthermore, this study showed that although acceleration and 100-m performance was about 20-25% lower on the treadmill than on 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 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 above 30 N), which corresponds to the biomechanical/muscular specific event of one leg push. Instantaneous data of vertical, horizontal and total GRF were averaged for each support phase (Fv, Fh and Ftot, 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 = Fh x V, expressed in W.kg⁻¹). Finally, Fv was specifically averaged for the five steps around top speed on the treadmill and reported as Fvmax.

Ratio of forces and index of force application / orientation
For each step, RF (in %) was calculated as the mean ratio of Fh to Ftot for one contact period. Further, we calculated an index of force application technique (DRF) representing the decrement in RF with increasing speed. Since with increasing speed the overall inclination of the body was expected to approach vertical, DRF 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 (Figure 3). Therefore, the higher the DRF value (i.e. a flat RF-speed relationship), the more RF is maintained despite increasing velocity. Conversely, subjects with a low DRF (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 Ftot that is directed forward, and DRF indicates how runners limit the decrease in RF with increasing speed during an acceleration run (or conversely how they maintain RF in order to produce high amounts of FH during their acceleration).

Field sprint performance
The 100-m sprints performance were measured by means of a radar Stalker ATS System™ (Radar Sales, Minneapolis, MN), which has been validated and used in previous human sprint running experiments (Chelly and Denis 2001; Di Prampero et al. 2005; Morin et al. 2006), to measure the 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’ CoM).

From these measurements, speed-time curves were plotted (Figure 4), and maximal running speed (Smax in m.s⁻¹) was obtained, as well as the 100-m time (t100 in s) and the corresponding 100-m mean velocity (S100 in m.s⁻¹). In addition, and in order to better analyze the 100-m performance, and compare the speed-time curves of subjects (Part 2 only), radar speed-time curves were fitted by a bi-exponential function (Morin and Sève 2011; Morin et al. 2006; Volkov and Lapin 1979):

\[ S(t) = S_{\text{max}} \left[ e^{\left(-\left(1+e^{S_{\text{max}}/\tau_2}\right)/\tau_1\right)} - e^{\left(-1/\tau_1\right)} \right] \]

\( \tau_1 \) and \( \tau_2 \) being respectively the time constant for acceleration and deceleration of this relationship, determined by iterative computerized 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 ± 0.08 m; 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 including sprints (e.g. soccer, basketball) in the six 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 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 athletic Tartan™ 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 one week prior to the testing session, subjects undertook a familiarization session during which they repeated treadmill sprints until being 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 6-s 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 100-m consisted in repeating the last part of the warm-up (from the three 6-s sprints on).

On the treadmill, subjects were tethered by means of 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.

**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 ± 8.4 kg; height 1.75 ± 0.08 m) who were all physically active and had all practiced physical activities including sprints (e.g. soccer, basketball) in the 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 ± 4.5 kg; height 1.83 ± 0.05 m). Their personal best times on 100-m (last update September 5th, 2011) ranged from 10.31 to 10.61 s. And one subject was a **world-class sprinter** (age: 21 yrs; body mass 81.0 kg; height 1.91 m). His official best performances were (last update September 5th, 2011): 9.92 s on the 100-m and 19.80 s on the 200-m. Among his official titles, he is French National Champion and record holder on 100-m and 200-m, he has won the World Junior Championships on 200-m in 2008, and has been European Champion in 2010 on 100-m, 200-m and 4x100-m relay. More recently, he finished at the 4th and 3rd place on 100-m and 200-m, respectively, at the 2011 World Championships in Athletics. All subjects gave their informed consent to participate in this study after being informed about the procedures approved by the local ethical committee and in agreement with the Declaration of Helsinki.

Non-specialist subjects performed these treadmill and field tests within a unique 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 official 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 were used 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 since it was not a complete push-off) to the step at top speed (Figure 3). The significance level was set at \( P < 0.05 \). The results of the 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.

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 (see Appendix).

On the track, subjects ran the 100-m in 13.40 ± 0.85 s (range: 11.90 - 15.01 s), which corresponded to \( S_{100} = 7.48 ± 0.48 \text{ m} \cdot \text{s}^{-1} \), for a top speed 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 100-m performance parameters: \( S_{\text{max}} \) and \( S_{100} \) (\( P < 0.01 \)), as was the mean value of \( H_{\text{Tht}} \) over the acceleration (\( P < 0.01 \)). Contrastingly, neither \( V_{\text{Ttc}} \) nor \( F_{\text{Tot}} \) averaged over the acceleration phase were correlated to these performance parameters.

An exception to this result was when \( V_{\text{Ttc}} \) was computed specifically at top speed on the treadmill: \( F_{\text{Ttc}} \cdot V_{\text{Tmax}} \) 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 \( F_{\text{Tot}} \) 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, field sprint performance (100-m time) was more than 2 SD better for CL (10.35 s) than for the national-level sprinters (10.92 ± 0.20 s), and much better than for the non-specialists (13.60 ± 0.70 s). 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 modeled speed-distance curves obtained during the 100-m.

The world-class sprinter tested differed substantially (more than 2 SD, Table 2) from his national-level counterparts for the maximal velocity and power output produced on the treadmill. Analysis of GRF showed that CL had remarkably higher values of \( H_{\text{Tht}} \) than the other individuals tested (Table 2), whereas his vertical and resultant force production per unit 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 \( H_{\text{Tht}} \) versus \( V_{\text{Ttc}} \) or \( F_{\text{Tot}} \) was accompanied by the ability to maintain higher values of \( H_{\text{Tht}} \) with increasing speed 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-speed linear relationships (from which \( D_{RF} \) is the slope) are detailed in Figure 5, in which one can observe the overall steeper RF-speed relationship (i.e. faster decrease in RF with increasing velocity) as subjects’ 100-m performance level lowers.

Last, 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 \( F_{\text{Tot}} \), which was only significantly correlated to \( S_{\text{max}} \) (\( P = 0.034 \)). For the components of this resultant GRF, \( H_{\text{Tht}} \) was significantly correlated to 100-m performance (\( P < 0.01 \)), whereas \( V_{\text{Ttc}} \) was only correlated to \( S_{\text{max}} \) (\( P = 0.039 \)), and not to \( S_{100} \).
Discussion

Overall, the main results of this project show that, as subjects’ level on 100-m increased, their ability to orient the resultant GRF generated by the lower limbs with a forward incline, i.e. to produce higher amounts of horizontal net force at each step increased. This was not the case of the total amount of force produced, or of the vertical component of the GRF. Indeed, 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 (100-m top and mean speeds). This was not the case for the vertical and resultant (total) forces produced. Thus, the way sprinters 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). 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 1920’s (Best and Partridge 1928; Furusawa et al. 1927) involving very fast runners (estimated 100-m time of ~10.8 s for subject H.A.R., probably 1928 Olympian sprinter Henry Argue Russel, in the study of Furusawa et al. (1927), many studies involved high-level and elite athletes (e.g. Bezodis et al. 2008; Karamanidis et al. 2011; Mero and Komi 1986) but not truly world-class sprinters.

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It is clear from the results section that the two Parts of this project essentially show similar results. For more clarity and a better reading, this discussion will respect the order of presentation of the methods and results of this project, and focus first on discussing the proof of concept and then the extension of the hypotheses to top level sprinters. Last, we will discuss the limits of our approach, which apply to both Parts of the project.

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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 and Janshen (2010) 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 1988), the calculated net horizontal and vertical forces were ~325 and 288 N, respectively. This corresponds to an estimated total force of ~434 N, and a RF of ~74.9 %. Our maximal values of RF are well in line with those of Kugler and Janshen (2010), but far below those of Mero (1988). This could be explained by the fact that contrary to our study and that of Kugler and Janshen (2010), 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.

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 speed on the treadmill ($F_{Vtc-V_{max}}$) was significantly linked to track $S_{max}$ ($P < 0.05$). This confirms results of Weyand et al. (2000), who showed a similar significant relationship between $F_{Vtc-V_{max}}$ 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 to 11.1 m.s$^{-1}$ vs. 7.80 to 9.96 m.s$^{-1}$). Our results confirm those of Weyand et al. (2000) 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 $F_{Hzt}$ is a key variable, but not $F_{Vtc}$.

The 100-m has often been described as a three-component race: acceleration phase, approximately constant top-speed phase and deceleration phase (Delecruise et al. 1995; Mero et al. 1992; Volkov and Lapin 1979). 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.

These results were obtained in low-level sprinters and in non-specialists. The following Part aimed at verifying their consistency in a much higher-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 100-m sprint performance.

First, the 100-m 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 normalized 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 the Part 2 of this project, we confirmed the significant and clear correlation between 100-m performance and average or maximal mechanical power normalized to body mass in the horizontal direction ($P < 0.01$), which was expected from previous findings (e.g. Cronin and Hansen 2005; Cronin and Sleivert 2005; Harris et al. 2008; Sleivert and Taingahue 2004), but the present study added to these data that mechanical power was this time measured during the specific sprint running exercise (Morin et al. 2010), contrary to the previously cited protocols in which power output was assessed during vertical, horizontal or incline push-offs, or cycling sprint. We also observed, as in the Part 1 of this project, a high and significant correlation between sprint performance and the ability to produce net horizontal force per unit 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 the 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 top speed (Table 3).
The specific data of CL presented in Table 2 indeed show that his $F_{\text{Hst}}$ and $D_{\text{RF}}$ is far better than that of his national level peers, yet his $F_{\text{tot}}$ value is within the range of that of his peers. To summarize, on average during a 6-s sprint on the treadmill, he was able to produce the same amount of $F_{\text{tot}}$ than national-level athletes (or even some of the non-specialists), but his outstanding ability to orient the resultant force with a forward incline led him to produce a $F_{\text{Hst}}$ 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 sprint running mechanics were investigated during sprints performed on an instrumented treadmill, and not overground. 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, Frishberg (1983) and Kivi et al. (2002) showed biomechanical differences between field and treadmill sprint running, whereas McKenna and Riches (2007) recently concluded that sprinting on a treadmill is similar to overground for the majority of the kinematic variables they studied, and specified that a motorized 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 speed on the treadmill, we can reasonably hypothesize 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 (Morin and Sève 2011). 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 $D_{\text{RF}}$ over the entire acceleration phase of a maximal 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 should have theoretically 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-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 (Morin and Sève 2011). 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 $F_{\text{Hst}}$ produced. This limit may not fundamentally challenge the proposed calculation of $D_{\text{RF}}$. 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 top speeds similar to those observed in the field (x-axis). Given that (i) $D_{\text{RF}}$ 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 about 6 to 8 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), $D_{\text{RF}}$ 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) to field $S_{\text{max}}$ 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 ($r = 0.899; \ p < 0.001$). We recently collected GRF data during 40-m sprints on a track (data and publications in process) in elite athletes, and the computations of RF and $D_{\text{RF}}$ basically show that (i) a linearity in the RF - speed is also observed and (ii) at top speed, a RF value of 0% (which is mechanically logical by definition) is reached.
Last, although measured and available in the published papers accompanying 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. 2011), and usually measured during overground sprints and often during competitions. Thus, we thought the treadmill measurements less qualitative and close to sprint 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 100-m performance is mainly associated with a higher ability to apply the resultant GRF vector with a forward orientation over the acceleration. Contrastingly, resultant GRF magnitude was not related to acceleration and overall 100-m performance, but only to top running speed. Further studies should focus on the necessity, effectiveness and practical feasibility of training programs / exercises that could develop the key variables of sprint performance put forward 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.

**Recommendations**

- The data put forward in this project suggest that 100-m sprint performance is closely related to the ability to produce a large amount of ground reaction force in the horizontal direction. Specifically, the world-class athlete tested did not show an outstanding capability of total force production. However, he was able to produce much more horizontal force than the other subjects (national-level sprinters and non-specialists), and especially at high running speeds.

- Contrastingly, the amount of resultant (total) force produced by the subjects was not related to their 100-m performance, and the amount of vertical force produced specifically at top speed was related only to the top speed reached on the field.

- Therefore, we can reasonably recommend that strength and conditioning of athletes should be oriented towards training this ability to limit the loss of RF during the acceleration phase.

- To do so, our thinking is that training could consider two possible ways of development: focusing on hip extensor muscles (mainly gluteus and hamstrings) for their role in the backward propulsion of the lower limb, especially as speed increases and the overall body position “verticalizes” and the ankle stabilizer muscles, for their contribution to transmit the force generated onto the ground. The latter work, especially at high speeds of motion, might be currently underestimated compared to maximal strength of the knee extensors or plantar flexors.

- These results may raise the question of the interest of a better-balanced strength-training regimen between the need for producing total force with the lower limbs, and efficiently transmitting it and orienting it forward during the support phase.