

SPRINT RUNNING MECHANICS

NEW TECHNOLOGY, NEW CONCEPTS, NEW PERSPECTIVES

– Written by Jean-Benoit Morin, France

Be it a direct (e.g. track and field events) or an indirect determinant of athletic performance (e.g. soccer, rugby, bobsleigh), sprint running is a key ability in many sports. For this reason, it is both the focus of specific training programmes and exercises, as well as a major cause of injuries. Further understanding of the mechanics of sprinting will surely help to design better training exercises to improve injury prevention and/or manage rehabilitation and return to sport strategies. The field of sport biomechanics, like other fields of sport science, is dependent on advances in the technology available to explore human locomotion. This is particularly important when studying sprinting i.e. an all-out ballistic activity that makes the human body move at speeds ranging 30 to 40 km/hour, making any direct biomechanical measurement rather challenging. A new device, the motorised instrumented sprint treadmill (IST), was first developed at the University of St-Etienne, France. This article will present the device, the new concepts and some of the results and new perspectives it has opened up in the fields of sport performance science, injury prevention and rehabilitation.

NEW TECHNOLOGY: THE INSTRUMENTED SPRINT TREADMILL

One step further

Parallel to the widely-used cycle ergometers, sprint treadmills were developed in the late 1980s and 1990s to measure propulsive power¹. This had the obvious advantage of being more realistic in assessing the physical capacities i.e. the athletic performance and muscular function of athletes. The main drawbacks of hitherto existing technologies were:

1. Force and velocity mechanical output was not measured at the same location (along the tether system by force transducers and at the foot, respectively).
2. The force along the tether which attached subjects to a fixed point behind them did not correspond exactly to the one produced at the foot (i.e. where velocity is measured).
3. The sampling rate was relatively low (one value each 0.25 seconds at best i.e. a sampling rate of 4 Hz), which may have interfered with the accurate determination of instantaneous maximal power.

4. Although various instrumented treadmills (i.e. Peter Weyand et al²⁻⁴) allow the achievement of top speeds similar to those reached over ground, record both ground reaction forces (GRF) and belt velocity at high sampling rates, only the vertical, but not the horizontal, component of the GRF signal can be computed.
5. Furthermore, these treadmills only allow subjects to use 'flying starts' when dropping onto the rolling treadmill and not typical sprint accelerations from null velocity.

In light of these limitations, we proposed a method based on an existing 3D-force dynamometer treadmill modified to enable sprint use and accurate force, velocity and propulsive power measurements. This was aimed at enabling an accurate assessment of the physical characteristics and performance of sprinters⁵. The IST (ADAL3D-WR, Medical Developpement, 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

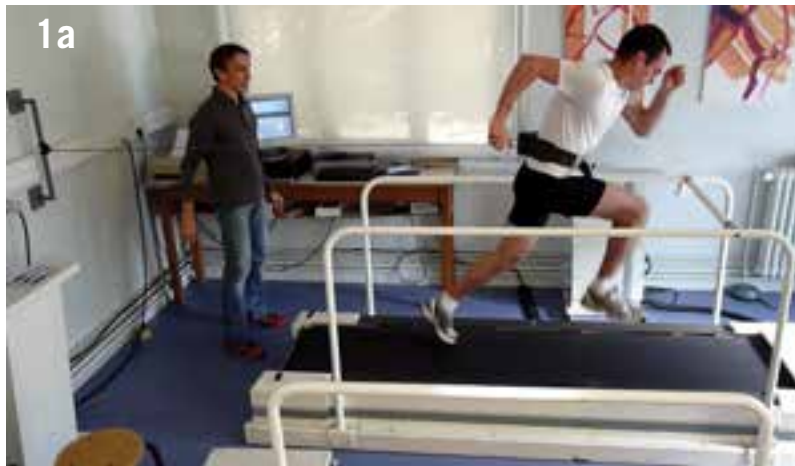


Figure 1: The instrumented sprint treadmill. Subjects are attached to a wall and can accelerate from a still crouched position. It is possible to synchronise electromyography measurements and video motion analysis. 1c) World-class sprinter Christophe Lemaitre sprinting on the treadmill.



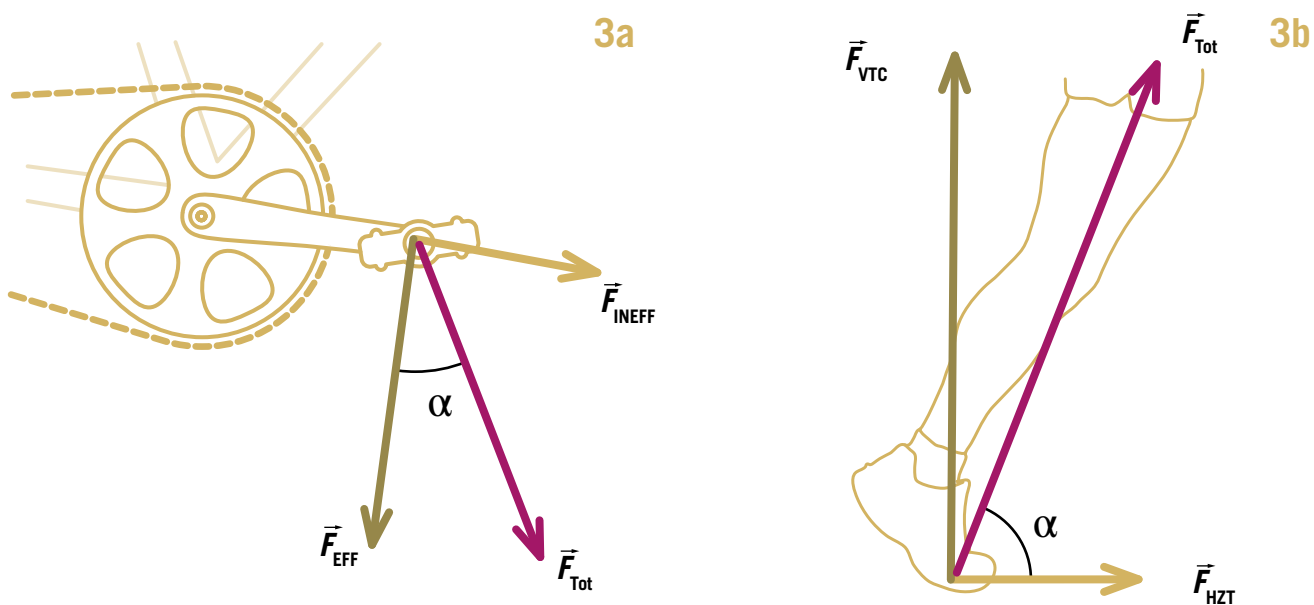
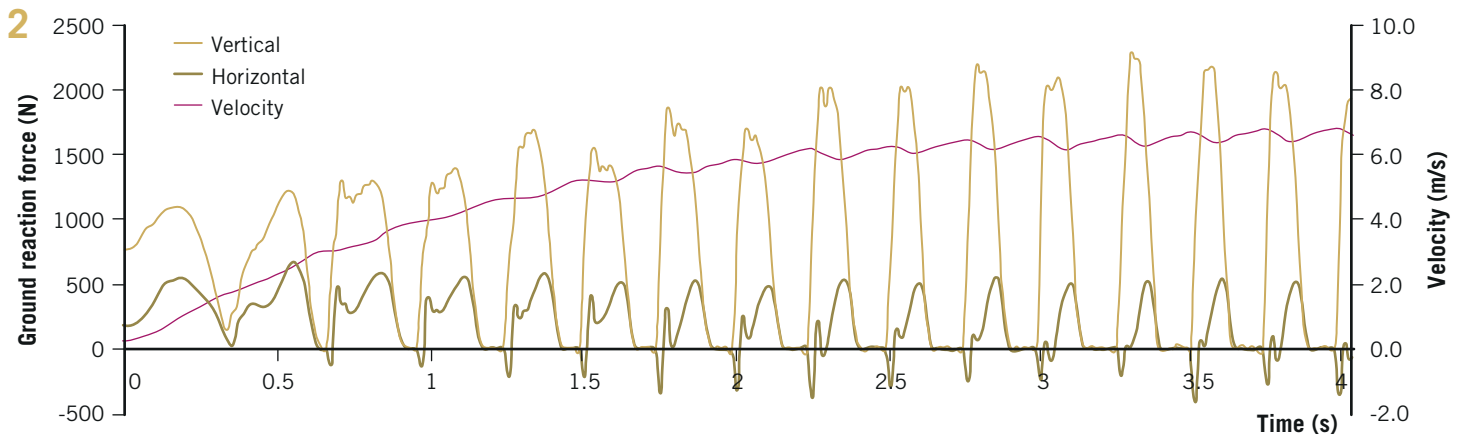
slab. It has been used for several years in the 'constant velocity' mode⁶ and recently upgraded to enable a 'constant motor torque' mode allowing athletes to perform sprints. The basic principle is that once the default motor torque is set and compensates for the friction induced by subjects' weight onto the belt, any horizontal net force applied induces an acceleration of the belt, whether it be positive (force applied in the forward-to-backward direction) or negative (push-off and braking forces, respectively). This device (Figure 1) allows an accurate reproduction of the starting technique at the beginning of the sprint i.e. subjects can lean forward in a still position as the treadmill belt is blocked and then released at the exact moment of the start.

MECHANICAL DATA AND MEASUREMENT CONDITIONS

With this treadmill, mechanical variables can be sampled at up to 1000 Hz over various sprint durations (including long sprints such as 200 or 400 m) and averaged for each contact period (force above 30 N), allowing to consider values averaged for each leg push-off. Vertical, horizontal (HF) and resultant (TOTF) GRFs and belt velocity (V) are measured and power in the horizontal direction is computed as the product of HF by V and expressed relatively to subjects' body mass. All these mechanical outputs may be averaged for the entire duration of a sprint and maximal instantaneous values may also be easily measured (Figure 2). Furthermore, the typical spatiotemporal

parameters of a running step can be easily determined: contact and aerial time, swing time of the leg and step frequency or length.

This motorised treadmill generates an additional motor torque in order to compensate for the friction due to subjects' weight. Typical velocities of about 6 to 8 m/second were observed on the IST, whereas about 9 to 11 m/second could be reached on a track. This discrepancy seems unavoidable with this kind of motorised treadmill, as shown in a comparative study⁷. This is mainly explained by the friction (and thus braking) applied to the belt during each step through the very intense vertical push produced. In this study, performance during a 100 m sprint performed on the treadmill was compared to that during a 100 m sprint



performed in the field (athletic track, radar measurements) in 12 well-trained subjects, including sprinters. It was concluded that both the maximal velocities and 100 m times differed between the treadmill and field (15 to 20%), but in a very similar way between subjects the speed time curves were very close in their overall shape and very similar when time and maximal velocity were normalised. Finally, but importantly, although there was a difference between the two modes, most of the performance variables (including maximal velocity and 100 m time) were significantly and highly correlated between field and treadmill.

Overall, it was considered that the inevitable differences between sprint performance on the IST and on the track are by far outweighed by the possibility to accurately and realistically study sprint mechanics. Noteworthy is the possible use

of the IST for sprint technique educative issues and for coaches and athletes (young or experienced) to work on the force application technique during sprint acceleration, as will be detailed later in this paper.

NEW CONCEPT: EFFECTIVENESS OF FORCE PRODUCTION APPLICATION

While the ability to run at high top speed has been clearly related to the ability to generate high amounts of GRF in the vertical direction^{3,4}, much less is known about the determinants of the acceleration phase of a sprint. Coaching practice has long considered the capability of force production as an inherent feature of acceleration and sprint capability. It is a common belief that how much force and impulse one athlete is able to produce and how hard they can 'push the ground' and 'push with a forward

Figure 2: Typical instantaneous signals of vertical and horizontal ground reaction forces and running velocity measured at a sampling rate of 1000 Hz on the instrumented sprint treadmill during a 4-second sprint.

Figure 3: Mechanical effectiveness of force application, from pedalling to sprint running. In pedalling (3a), effectiveness is computed as the ratio 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. In sprint running (3b), the analogy we propose here gives effectiveness as the ratio $RF = F_{HT} / F_{TOT}$. The analogy is not complete because in running, the other component (F_{VTC}) is not useless.

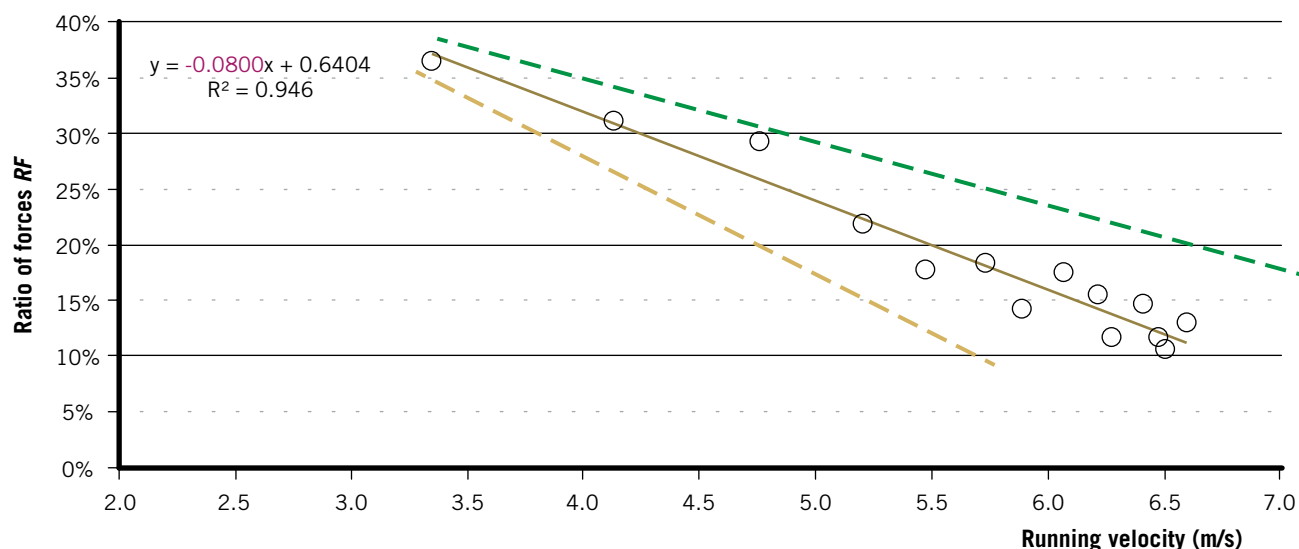


Figure 4: Ratio of forces and index of force orientation D_{RF} . This typical example (non-specialist; body mass 68.1 kg) of the RF -speed linear relationship obtained during a 6-second sprint on the instrumented sprint treadmill. Each point corresponds to values of RF and running speed averaged for 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 worse index for the golden line (steeper relationship i.e. the horizontal force drops faster as speed increases).

incline' during the entire acceleration phase are key variables.

Mathematically, as explained in Figure 3, the angle of the resultant GRF vector determines the values of its horizontal and vertical components for a given amount of GRF. As previously proposed in pedalling mechanics⁸ 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'. Using this analogy with pedalling mechanics, we proposed to calculate, for each step, the ratio of force (RF) as the ratio of the contact-averaged HF to the corresponding resultant GRF (TOTF). The higher the RF , the higher the horizontal force produced for a given amount of total (resultant) force.

In most of the subjects tested, a systematic linear decrease of RF was observed with increasing speed during sprint acceleration (Figure 4). An index of force application technique, decrement in the ratio of force (DRF), was calculated, representing this decrement in RF with increasing speed. DRF is computed as the slope of the linear RF -speed relationship between the second step and the step at top speed (Figure 4). Therefore, the higher the DRF value (i.e. a flat RF -speed relationship), the more RF is maintained despite increasing velocity (and vice versa). In other words, RF represents the part of TOTF 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 HF during their acceleration. We therefore hypothesised that the DRF index 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.

One may wonder whether these measurements and mechanical concepts are typical to treadmill sprints only and whether they also characterise track sprinting. This issue is of importance when transferring treadmill results to the real world of sport performance. To answer this question, a collaborative study with the French National Institute of Sport and Performance (Paris) was recently performed in which GRF data was collected in elite sprinters during 40 m maximal sprints on a track embedded with force plates. The results of this study, which is currently under publication, showed that during track sprint acceleration, similar values of GRF and RF were observed (as on the IST), as were linear RF -speed relationships and even very similar values of DRF .

RELATIONSHIP WITH SPRINT ACCELERATION AND PERFORMANCE

To evaluate the importance of the effectiveness of ground force application to maximise sprint performance, 10 male athletes were involved in sprinting

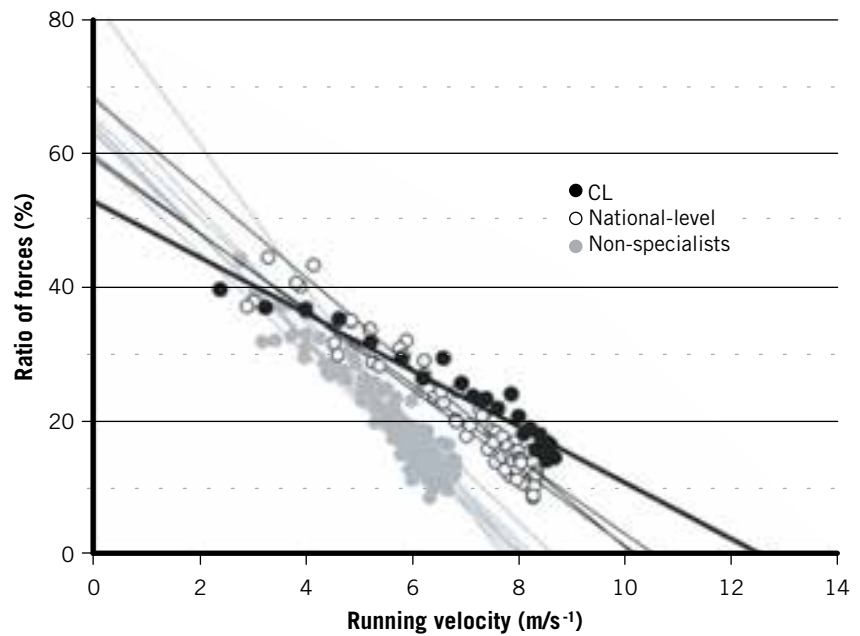
activities (soccer, rugby and basketball) and two national-level long jump competitors were tested on the IST and on the track. It was found that the DRF was significantly and highly correlated to the two main 100 m performance parameters: mean and maximal 100 m velocity, as was the mean value of HF over the entire acceleration⁹. In contrast, neither vertical nor TOTF averaged over the acceleration phase were significantly correlated to these performance parameters. Further, subjects' TOTF was not significantly correlated to DRF . It was concluded that the force application technique, as opposed to the amount of total force subjects are able to apply onto the ground, is a key determinant of field 100 m sprint performance. However, one limitation of this study was that the results were obtained in low-level sprinters and in non-specialists. A subsequent study aimed at verifying whether these conclusions hold true in a group of elite sprinters.

EXTENSION TO NATIONAL ELITE AND WORLD-CLASS ATHLETES

Using the same experimental design¹⁰ (i.e. 6 second sprint on the IST and field 100 m test), three types of subjects were compared:

1. Nine physical education students who had practiced physical activities including sprints (e.g. soccer, basketball), in the 6 months preceding the study, but were not sprint specialists.

Figure 5: Individual *RF*-velocity linear relationships during the acceleration phase of the treadmill sprint for the three populations compared. At high velocities (>6 m/second), 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/second on the treadmill) and the world-class sprinter (CL) more than his national-level peers.



2. Three French national-level sprinters with personal best times in 100 m ranging from 10.31 s to 10.61 seconds.
3. A world-class sprinter whose official best performances are: 9.92 seconds in the 100 m and 19.80 seconds in the 200 m.

The results clearly showed that the world-class sprinter produced remarkably higher values of HF than the other individuals, whereas his vertical and resultant force production relative to bodyweight were in the range of those displayed by his national-level counterparts (yet much higher than for the non-specialists group). Not only did the world-class sprinter produce higher amounts of HF versus vertical or

TOTF, but he was also able to maintain higher values of HF with increasing speed during acceleration on the treadmill. This is illustrated by the DRF index, which was 42.9% higher than the average value for national-level sprinters and 95.2% higher than the average value of non-specialists. Individual *RF*-velocity linear relationships (from which DRF is the slope) are detailed in Figure 5. One interesting observation was the overall steeper *RF*-velocity relationship (i.e. faster decrease in *RF* with increasing velocity) as 100 m performance decreased. These results, obtained in high and top-level specialists, clearly confirm those obtained in the previous study. The better ability to produce and apply high HF 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 and not from their ability to generate high amounts of TOTF. Furthermore, the only performance parameter significantly related to the vertical or resultant force production was top speed, as previously observed^{3,4}.

It seems that the mechanical explanation of the 100 m performances of the world-class sprinter tested was that on average, during a 6 second sprint on the treadmill, he was only able to produce the same amount of TOTF as national-level athletes (or even some of the non-specialists). However, his outstanding ability to orient the resultant force with a forward incline led him to produce a HF that was 12% higher than his national-level counterparts (one of them is a member of the national 4 × 100 m relay team) and 22% higher than for non-specialists.

Overall, the main and very novel results of these two studies show that 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 represent two distinct skills. The next and last section of this article widens the interest of using the IST to monitor sprint mechanics and performance in order to potentially help prevent injuries or handle their rehabilitation process.

“**A better-balanced training should consider how force is transmitted to the supporting ground, not only how much force is produced**”

NEW PERSPECTIVES: SPORT SCIENCE AND MEDICINE

From performance factors to injury prevention: the pivotal role of the hamstring muscles

In our research group, sport scientists and medical doctors collaborate and ‘explosive’ sports such as sprinting, soccer or rugby are seen from both a biomechanical and an injury prevention/treatment point of view. Athletes are usually screened for their force production capacity or their ability to orient force during the acceleration phase (first parts of this article). Unfortunately, they are also studied because they get injured or re-injured. Most of the time, in such sports, hamstring muscle injuries (one of the most common and recurring non-contact injuries) are involved. Therefore, we asked ourselves:

What were the mechanisms (anatomical and/or neuromuscular) affecting the world-class athlete?

When tested, they produced larger HF, but similar TOTF to their lower-level counterparts while accelerating. Based on this observation the ‘hip extensors hypothesis’ was formulated.

Figure 5 shows that a typical characteristic of the world-class sprinter is his ratio of force when running speed is high. This is interpreted as an ability to produce more horizontally-oriented GRF at high running speeds i.e. by definition, at a moment of the sprint when the overall position of the body is mainly vertical, contrary to the early phase of the acceleration during which this position is more crouched. Therefore, the hypothesis is that the only possible way to produce high amounts of horizontally oriented GRF during a running step in such conditions is to have strong hip extensor muscles (mainly hamstring and gluteus muscles) and/or be able to activate them in a much more effective way. This ‘hip extensor hypothesis’, if validated, would have two consequences:

1. it would place a specific focus on this muscle group in the specific training programme of the athlete (in contrast with the classically ‘overdeveloped’ knee extensor and hip flexor musculature), and
2. it would also confirm the significant level of attention that should be paid to this muscle group when implementing a

sprint-related muscle injury prevention programme.

It is believed that these two points should support a better-balanced training programme of the anterior and posterior muscle chains.

This could be a ‘win-win’ strategy on both performance and injury prevention ends of the problem. This work could bring support to the need of a better focus of strength training on:

1. Hip extensor muscles (mainly glutei and hamstrings) for their role in the backward propulsion of the lower limb, especially as speed increases and the overall body position ‘verticalises’.
2. The ankle stabiliser 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. Since “a chain is only as strong as its weakest link”, a better balanced strength training regimen could be considered, between the need for a high total force of the lower limbs



and an efficient application of this force during the support phase.

This hypothesis has recently been tested in a group of athletes used to sprinting (sprinters, rugby or soccer players). They performed a series of 12 maximal 6 second sprints on the IST with only 24 seconds of passive rest between sprints. The mechanical data detailed above were time synchronised with electromyographical measurements of the main knee extensor, flexor, plantar extensor, flexor and gluteus muscles. Each measurement of concentric and eccentric force production at the hip and knee was performed in isokinetic conditions immediately before and after the sprint series. With this protocol design, the questions of whether subjects producing the highest amounts of HF on the treadmill (and having the best DRF indices) are also those whose hip extensor muscle capabilities are the highest and/or those who are able to activate these muscles at the highest level both before (swing phase of the leg) and during the contact phase of the foot onto the ground during maximal sprints, were answered. The latter point about the moment of the sprint stride cycle at which the hamstring muscles are at the highest risk of injury (end of the swing phase vs beginning of the contact phase) is a source of debate^{11,12}. Lastly, studying the changes in all these variables with fatigue (exhausting 12 sprint series) may allow us to put forward even more specific information about the effect of sprint fatigue on force production and muscle activation. The preliminary results of this study basically show that HF is significantly correlated to hamstring muscle eccentric force capability and their level of activity before contact with the ground, which partially validates our 'hip extensor hypothesis', and brings new insights into both sprint performance and hamstring injury prevention.

SUMMARY

Until new data is presented and fully equipped tracks are made available to scientists and athletics coaches, the instrumented sprint treadmill highlighted in this paper is the only device allowing for an accurate quantification of tri-

dimensional ground reaction forces for all the steps of typical sprint acceleration. It allows us to present the concept of mechanical effectiveness of ground reaction force orientation/application and to show that this ability is better-related to acceleration and sprint performance than the physical capability of total force production, even in world-class athletes. Unpublished data (work in progress) obtained with track-embedded force plates during track sprinting showed that data collected on the treadmill is very close to field-collected data. Finally, the crucial role of hamstring muscles in sprint performance and also risk of injury is a topic of interest for both sports science and sports medicine professionals. Beyond the passion for sport performance and health, the common point we researchers and doctors share in this project is the new technology introduced in this article.

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Jean-Benoit Morin Ph.D.
Locomotion and Sports Biomechanics
Laboratory of Exercise Physiology
University of Saint-Etienne
Saint-Etienne, France
Contact:
jean.benoit.morin@univ-st-etienne.fr