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ORIGINAL ARTICLE

Sprint running performance: comparison between treadmill and field conditions

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Abstract We investigated the differences in performance between 100-m sprints performed on a sprint treadmill recently validated versus on a standard track. To date, studies comparing overground and treadmill running have mainly focused on constant and not maximal "free" running speed, and compared running kinetics and kinematics over a limited number of steps, but not overall sprint performance. Eleven male physical education students including two sprinters performed one 100-m on the treadmill and one on a standard athletics track in a randomized order, separated by 30 min. Performance data were derived in both cases from speed–time relationships measured with a radar and with the instrumented sprint treadmill, which allowed subjects to run and produce speed "freely", i.e. with no predetermined belt speed imposed. Field and treadmill typical speed–distance curves and data of maximal and mean speed, 100-m time and acceleration/deceleration time constants were compared using *t* tests and field–treadmill correlations were tested. All the performance parameters but time to reach top speed and deceleration time constant differed significantly, by about 20% on average, between field and treadmill (e.g. top speed of 8.84 ± 0.51 vs. 6.90 ± 0.39 m s^{-1}). However, significant correlations were found ($r > 0.63$; $P < 0.05$) for all the performance parameters except time to reach top speed. Treadmill and field 100-m sprint performances are different, despite the fact that subjects could freely accelerate the belt. However, the significant correlations found make it possible to investigate and interpret inter-individual differences in field performance from treadmill measurements.

Keywords Top speed · 100-m · Acceleration · Ergometer

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Introduction

Treadmills have long been used to investigate walking and running locomotion and monitor physical rehabilitation. Their main interest is that they allow a high level of standardization and convenience of measurements in research laboratory and/or medical context. Further, in the field of research on human locomotion and exercise physiology, they allow subjects to perform and be studied while walking or running in place, the supporting ground (i.e. the treadmill belt) being the element moving relatively to subjects' centre of mass (CM). Consequently, and because this situation is almost the opposite of real world biped locomotion (in which subjects' CM moves relatively to the supporting ground), studies have investigated the differences between field and treadmill conditions in the past 40 years or so (e.g. Nigg et al. 1995).

These comparative studies were basically aimed at answering the question as to whether overground locomotion could be interpreted/investigated in light of the measurements performed on treadmills. The main limit of existing studies is that they investigated various kinetic and kinematic parameters, but reported some contradicting results. Further, low-speed and high-speed (sprint) running should be distinguished.

In studies comparing overground and treadmill running at low speeds, Van Ingen Schenau (1980) showed that the mechanics of running were basically similar provided that the belt speed was constant and a coordinate system moving with the belt was used. This overall similarity was also supported by other studies (e.g. Williams 1985; Kram et al. 1998; Riley et al. 2008; Schache et al. 2001). In contrast, several studies reported significant differences between the two conditions (e.g. Nelson et al. 1972; Dal Monte et al. 1973; Elliot and Blanksby 1976; Nigg et al. 1995).

When focusing on sprint (i.e. maximal speed) running, contradicting results have also been reported. 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 was similar to overground sprinting 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.

As detailed in this brief overview of literature, whatever the level of running speed considered, field–treadmill comparison studies did not reach a consensus, but all these studies have in common the following limits. First, mainly for technical and methodological reasons (video analysis and inverse dynamics), the sample of data used for these comparisons systematically consists of one to four steps/strides at most (Frishberg 1983; Kivi et al. 2002; McKenna and Riches 2007; Riley et al. 2008). Consequently, kinetic and kinematic variables are compared on the basis of only a few number of steps and at specific velocities that are not systematically maximal (Kivi et al. 2002; McKenna and Riches 2007; Nigg et al. 1995; Riley et al. 2008; Schache et al. 2001).

Second, the sprint running speed was imposed on the subjects either to match the one previously measured in the field or from the treadmill motor setting high-to-maximal speed, but constant speed. An example of the first type of setting is given in the study of Frishberg (1983), who recorded a typical sprint performance (a 91.44-m sprint) through 9.14-m sections in order to set the speed of the treadmill belt with corresponding increasing values (one mean 9.14-m constant speed value for every span corresponding to those covered in field conditions). The second type of setting typically requires subjects to run at constant velocities either corresponding to their maximal speed recorded beforehand during field measurements (e.g. (Frishberg 1983; Kivi et al. 2002) or to the maximal speed they are able to maintain for a few steps performed after a lowering movement from the handrails onto the moving treadmill belt (e.g. Bundle et al. 2003, 2006; Kivi et al. 2002; Weyand et al. 2000). Both these settings do not exactly reproduce "free" sprint running on the field during which the runner's speed constantly changes as a function of the amount of force applied onto the supporting ground, and over a typical acceleration phase. During acceleration, the speed increases from null to maximal speed, and thus by definition with no constant speed phase in between. Bowtell et al. (2009) recently proposed that such a fundamental basic of field sprinting mechanics should be respected in treadmill conditions to better simulate field sprint. Basically, subjects (through their muscular actions) should "command" the belt speed, not the other way round: "to measure peak performance there is a requirement for a runner to speedup and slowdown as they want and the speed of the treadmill belt should be capable of responding adequately and consistently" (Bowtell et al. 2009).

Last but not least, though Lakomy (1987) reported a comparison of mean and peak speeds during 30-s field and treadmill sprints, no study has specifically approached field–treadmill sprint comparisons from the performance standpoint. Indeed, except for maximal speed, which is sometimes investigated, studies have focussed on specific kinetic and kinematic parameters and not on overall sprint performance. By sprint performance, we mean the mechanical output in terms of speed–time and distance–time relationships, which are the variables firstly and mainly quantified in sprint running (be it competitive or not). For instance, time to cover a given distance is the main variable retained in our current mode of judging athletics performance. On the 100-m, and on some top-level occasions, mean and instantaneous speeds are measured/reported (e.g. Brüggemann et al. 1999), and the shapes of speed–time curves and acceleration/deceleration phases discussed (e.g. Arsac and Locatelli 2002; Beneke and Taylor 2010). Therefore, we will focus in the present study on these performance variables, and investigate whether field performance over an entire sprint could be appropriately simulated on a treadmill.

Following the recent recommendations for studying the entire acceleration phase and using motorized treadmills (McKenna and Riches 2007) allowing free sprint running, i.e. with no predetermined belt speed (Bowtell et al. 2009), we recently presented an instrumented motorized treadmill for sprint use (Morin et al. 2010). This device allows subjects to accelerate the treadmill belt from a standing start-up to the plateau of maximal speed and further in case of long sprints. The only additional help to subjects' effort is the constant motor torque necessary to overcome the friction caused by subjects' body weight on the belt. Thus, given (a) the above-mentioned limitations of existing studies, and (b) the characteristics of this treadmill, we thought it would be of interest to use this device to investigate the similarities between overground and sprint running performance over a typical distance of 100 m.

The aim of the present study was therefore to compare overground and treadmill sprint running performance through the variables derived from speed–time and speed–distance relationships, i.e. maximal and mean speeds, 100-m time, and the characteristics of acceleration and deceleration phases.

Methods

Subjects and experimental protocol

Eleven subjects (body mass (mean ± SD) 70.4 ± 5.8 kg; height 1.77 ± 0.05 m; age 24.4 ± 3.9 years) volunteered to participate in this study. They were all physical education students and physically active, and had all practised physical activities including sprints (e.g. soccer, basketball) in the 6 months preceding the study. Two subjects were national level long jump and sprint competitors (100-m personal best 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 comparison protocol consisted in performing one 100 m on the treadmill and one on a standard athletic Tartan™ track. The two sprints were performed in a randomized counterbalanced order (six subjects began with the treadmill 100 m) and separated by 30 min of passive rest, in similar ambient temperature conditions. Subjects wore the same outfit and shoes in both conditions. Whether the field or the treadmill 100 m was performed first, the warm-up was similar and consisted in 5 min of low-pace (~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 100-m sprint. The warm-up preceding the second 100-m sprint (be it on the treadmill or on the track) consisted in repeating the last part of the warm-up (from the three 6-s sprints).

Field measurements

The 100-m sprints were performed from a standing start (crouched position similar to that on the treadmill), and performance was measured by means of a radar Stalker ATS System™ (Radar Sales, Minneapolis, MN). This device has been validated and used in previous human sprint running experiments (Chelly and Denis 2001; Di Prampero et al. 2005; Morin et al. 2006) and measures 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' CM).

From these measurements, speed–time curves were plotted (Fig. 1), and maximal running speed (S_{max} in m s^{-1}) and time to reach S_{max} (tS_{max} in s) were obtained, as well as the 100-m time (t_{100} in s) and the corresponding mean 100-m speed (S_{100} in m s^{-1}). To better analyse the 100-m performance and especially the acceleration and deceleration characteristics of each sprint, speed–time curves were then fitted by a biexponential function (Henry 1954; Morin et al. 2006; Volkov and Lapin 1979):

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

τ_1 and τ_2 being, respectively, the time constant for acceleration and deceleration of this relationship (expressed in s), determined by the least square method. Speed–distance curves (Fig. 1) were then obtained from speed–time curves by simple time integration of modelled speed data.

Treadmill measurements

The motorized instrumented treadmill (ADAL3D-WR, Medical Developpement—HEF Tecmachine, Andrézieux-Bouthéon, France) used has been recently validated for sprint use [for full details, see (Morin et al. 2010)]. It is mounted on a highly rigid metal frame fixed to the ground

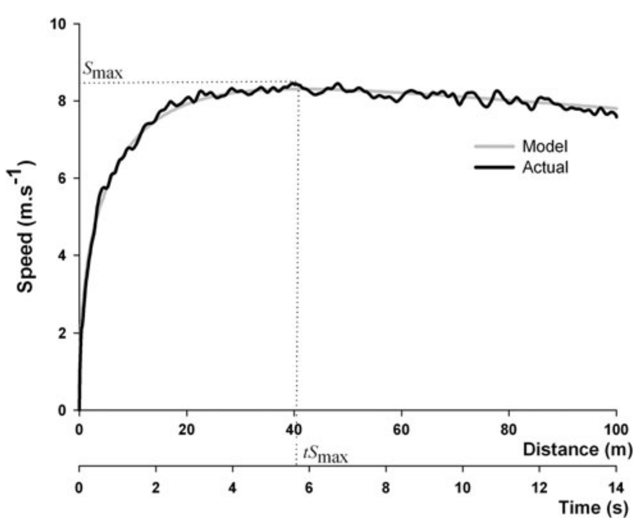

Fig. 1 Typical speed–time curve measured by the radar (*black line*) and modelled by the biexponential equation (*grey line*). In this typical example (the subject is a basketball player, 1.80 m; 80 kg): $S_{max} = 8.46$ m s^{-1}, $tS_{max} = 5.95$ s, $\tau_1 = 1.48$ s, $\tau_2 = 92.9$ s, $t_{100} = 13.44$ s and $S_{100} = 7.44$ m s^{-1}. The biexponential equation fitting this typical speed–time curve at best is $S(t) = 8.46\left[e^{((-t+5.95)/92.9)} - e^{(-t/1.48)}\right]$. The coefficient of correlation between actual and modelled data of speed was $r = 0.997$

through four piezoelectric force transducers (KI 9077b, Kistler, Winterthur, Switzerland) and installed on a specially engineered concrete slab to ensure maximal rigidity of the supporting ground.

The constant motor torque was set to 160% of the default torque, i.e. the motor torque necessary to overcome the friction on the belt due to subject's body weight. The default torque was measured by requiring the subject to stand still at the centre of the treadmill and by increasing the driving torque value until observing a movement of the belt greater than 2 cm over 5 s. This default torque setting as a function of belt friction is in line with previous motorized treadmill studies (Chelly and Denis 2001; Falk et al. 1996; Jaskolski et al. 1996; Jaskoska et al. 1999) and with the detailed discussion by McKenna and Riches in their recent study comparing "torque treadmill" sprint to overground sprint (McKenna and Riches 2007). The motor torque of 160% of the default value was selected after several preliminary measurements (data not shown) comparing various torques, because (a) it allowed subjects to sprint in a comfortable manner and produce their maximal effort without risking loss of balance, and (b) higher torques (180 and 200%) caused loss of balance in some of the subjects. This prevented them, even after the longer familiarization necessary in such conditions, to sprint with the overall sprint technique they are used to on the field.

Subjects were tethered by means of a leather weightlifting belt and a stiff thin rope (0.6 cm in diameter), itself attached to a 0.4-m vertical metal rail, rigidly anchored to the wall behind the subjects. The horizontal distance between the wall and the subjects' ends of the rope was ~2 m. This system allowed (a) individual setting of the height of the wall-mounted fixation for a horizontal position of the rope, (b) subjects to run at the same horizontal position along the treadmill, and (c) running at a horizontal distance (2 m) that reduced the ratio of the vertical component of the wall reaction force to the propulsive force. When correctly attached, subjects were required to lean a little bit forward in a typical sprint start position (standardized for all subjects) with their preferred foot forward. After a 3-s countdown, the treadmill was released, and the belt began to accelerate as subjects applied fore–aft force. On the field as well as on the treadmill, subjects were encouraged throughout the 100-m sprint.

Mechanical data were sampled at 1,000 Hz during a 30-s period, which included the 100-m, allowing determining the beginning of the sprint as the moment when the belt speed exceeded a value of 0.2 m s^{-1}. After appropriate filtering (Butterworth-type 30 Hz low-pass filter), instantaneous values of ground reaction forces and belt speed were averaged for each contact period (vertical force above 30 N). Then, instantaneous speed (S in m s^{-1}) was averaged for each contact period, which corresponded to the biomechanical and muscular-specific event of one leg push (Martin et al. 1997), and maximum average value for the 100 m was retained for analysis as S_{max}.

The 100-m distance was checked during the sprint by means of a wheel odometer placed in contact with the treadmill belt, at the back end of the treadmill. The individual exact time–distance curves were then computed a posteriori from instantaneous speed–time relationships. As shown in Fig. 2, the instantaneous speed–time curves allowed the same biexponential modelling as in field conditions and, thus, the same performance variables, i.e. S_{max}, tS_{max}, t_{100}, S_{100}, τ_1 and τ_2 to be determined.

Last, in order to discuss the differences or similarities between 100-m performances in field and treadmill conditions in light of the main physical capacities and mechanical output of the subjects, instantaneous data of

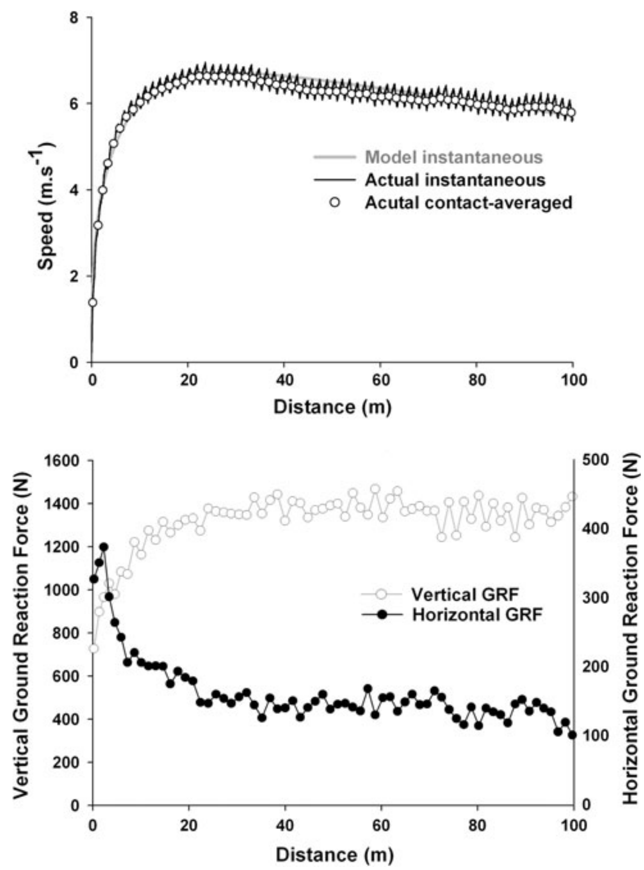

Fig. 2 *Upper panel* typical speed–time curve obtained on the treadmill for the typical subject mentioned in Fig. 1. Speed data are reported as instantaneous actual (*black line*) and modelled (*grey line*) values, and as values averaged for each contact phase during the 100-m sprint (*circles*). The biexponential equation fitting this typical speed–time curve at best is $S(t) = 6.96\left[e^{((-t+4.61)/62.8)} - e^{(-t/1.43)}\right]$. The coefficient of correlation between actual and modelled data of speed was $r = 0.993$. *Lower panel* values of vertical (*black circles*) and net horizontal (*white circles*) ground reaction forces averaged for each contact phase during the 100-m sprint for the typical subject mentioned in Fig. 1

vertical (Fv) and net horizontal force (Fh) and horizontal power (Ph in W/kg) were averaged for each contact period (Fig. 2) and measured along with the main running step kinematics: contact time (t_c in s), aerial time (t_a in s) and step frequency (f in Hz).

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, and the mechanical variables studied were compared between treadmill and field conditions using t tests and Pearson's correlations. The quality of the fitting of speed–time curves by the biexponential equation was tested by means of Pearson's correlations computed between instantaneous values of actual and predicted speed, in both treadmill and field conditions. The significant level was set at $P < 0.05$.

Results

As shown in Table 1, most of the performance parameters differed significantly between track and treadmill conditions, i.e. t_{100}, S_{100}, S_{max}, and τ_1, with a non-significant tendency for tS_{max} ($P = 0.071$). These differences all characterized an overall lower performance in treadmill condition. The correlations between these two sets of data were significant (correlation coefficients ranging from $r = 0.63$ to $r = 0.89$; $P < 0.05$; Fig. 3) for all of the parameters studied, except tS_{max}.

The typical speed–distance curves shown in Fig. 4 show that despite the almost constant (about 20%) difference over the 100-m sprint, their overall shape is basically similar, which is confirmed by the significant correlation ($P < 0.05$; Table 1) found between the three variables setting the overall shape: S_{max}, τ_1 and τ_2. Further, the quality of the fitting of speed–time curves by the biexponential model equation was very high both on track or treadmill ($r > 0.956$; $P < 0.01$ for all conditions).

Step-averaged values of Fv and Fh were 1,108 ± 121 and 228 ± 29 N, respectively, and Ph was 17.3 ± 2.8 W kg^{-1}. The main step kinematics were $t_c = 0.150 \pm 0.02$ s, $t_a = 0.150 \pm 0.02$ s and $f = 3.00 \pm 0.24$ Hz (values averaged over the entire 100 m).

Discussion

The main result of this study is that 100-m sprint performance variables were different between treadmill and field conditions (by ~20% on average) except for the time constant for deceleration. These differences all characterized a lower performance on the treadmill compared to field sprint running. However, speed–distance curves are similar in their overall shape, and all the performance variables but tS_{max} were significantly correlated ($P < 0.05$).

Performance data obtained on the track are in line with previous studies led in similar populations, i.e. S_{100} and S_{max} (Best and Partridge 1928; Bowtell et al. 2009; Chelly and Denis 2001; Falk et al. 1996; Lakomy 1987; McKenna and Riches 2007; Morin et al. 2006; Volkov and Lapin 1979), and τ_1 (Di Prampero et al. 2005; Morin et al. 2006; Volkov and Lapin 1979) were close to values reported in previous studies, whereas τ_2 was lower in this study than for Morin et al. (2006): 73.4 ± 26.8 versus 128 ± 94 s, but the latter study was conducted in less skilled subjects, as shown by their 100-m performance (14.21 ± 0.79 s), i.e. ~1 s longer than in this study.

The comparison of data with previous treadmill studies is rather limited since (a) some of them used motorized treadmills and some others did not, (b) no study used the same instrumented sprint treadmill as the present one (except Morin et al. 2010) and hence different characteristics of the measuring device itself, and (c) only Bowtell et al. (2009) and Morin et al. (2010) used a treadmill with no pre-determined belt speed that reacted to subjects' propulsive actions, such as in this study. However, the maximal speed values we report are comparable, though

Table 1 Comparison of performance variables for field and treadmill conditions and correlations between values for the two conditions

Variable	Field	Treadmill	t test P values	Absolute % difference	r	Correlation P values
t_{100} (s)	13.25 ± 0.71	17.0 ± 1.01	**<0.001**	28.3 ± 4.54	**0.81**	**<0.01**
S_{100} (m s^{-1})	7.57 ± 0.42	5.90 ± 0.36	**<0.001**	22.0 ± 2.79	**0.82**	**<0.01**
S_{max} (m s^{-1})	8.84 ± 0.51	6.90 ± 0.39	**<0.001**	21.9 ± 2.15	**0.89**	**<0.001**
tS_{max} (s)	6.21 ± 1.43	5.12 ± 1.05	0.071	13.1 ± 27.3	−0.01	0.98
τ_1 (s)	1.94 ± 0.38	1.60 ± 0.20	**<0.01**	15.5 ± 13.0	**0.63**	**<0.05**
τ_2 (s)	73.4 ± 26.8	69.7 ± 17.2	0.49	0.29 ± 24.0	**0.76**	**<0.01**

Values are mean ± SD. Bold values indicate significant differences (field vs. treadmill) or correlations

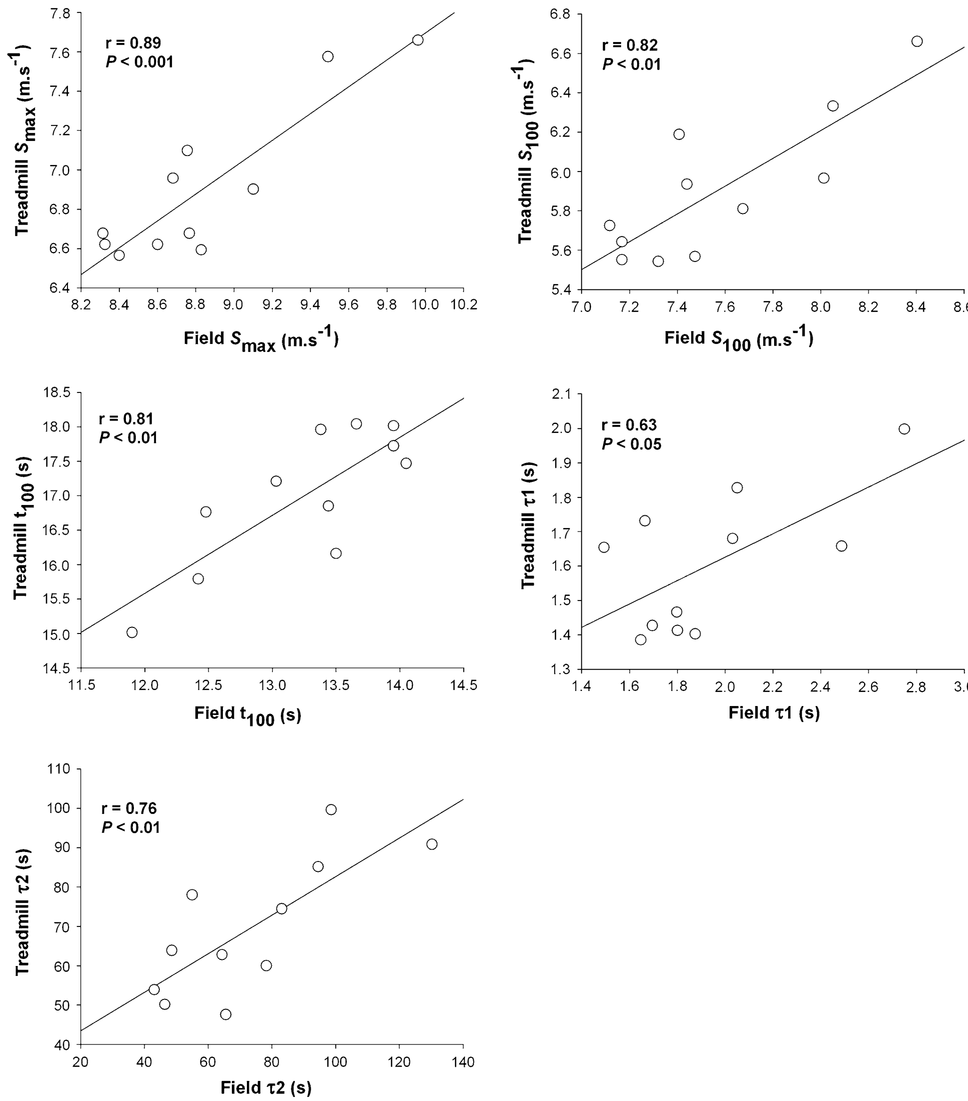

Fig. 3 Correlations between field and treadmill performance parameters

slightly lower than those of Bowtell et al. (2009): 6.90 ± 0.39 versus 7.92 ± 0.27 m s^{-1}, and higher than those of Morin et al. (2010): 6.90 ± 0.39 versus 5.91 ± 0.46 m s^{-1}, which seems logical since in their study, they set a motor torque of only 120% of the default torque (vs. 160% in the present study) in order to allow subjects to reach their maximal power, and not maximal speed. Nevertheless, our data of treadmill S_{max} are well in the range of those previously reported in several similar experiments (Bundle et al. 2003; Chelly and Denis 2001; Frishberg 1983; Lakomy 1987; McKenna and Riches 2007; Weyand and Bundle 2005; Weyand et al. 2000, 2009, 2010), whatever the treadmill and protocol used (ranging from 6.1 m s^{-1} for Chelly and Denis 2001) to 11.1 m s^{-1} for (Weyand et al. 2000), with a grand average among studies of ~8.5 m s^{-1}).

When focusing on the few studies that specifically investigated or reported among other results field–treadmill comparisons of sprint mechanics and S_{max} as the only performance variable, some report significant differences (Frishberg 1983; Kivi et al. 2002) and/or lower performance on the treadmill (Chelly and Denis 2001; Lakomy 1987) and less often a higher one (by 11.5% on average for Bowtell et al. 2009), whereas McKenna and Riches (2007) report no fundamental difference between field and treadmill conditions. Last, Frishberg (1983) showed no difference in S_{max} between field and treadmill, but this was very likely due to the fact that treadmill speed was determined and set from individual values of field S_{max} in these studies. To our knowledge, only Bundle et al. (2003) reported similar values of track and treadmill S_{max}, but not after a typical acceleration phase. Indeed, they used a specific experimental procedure in which subjects lowered them from the handrails onto the belt, already rolling at high speeds, up to the maximal speed they could handle that way.

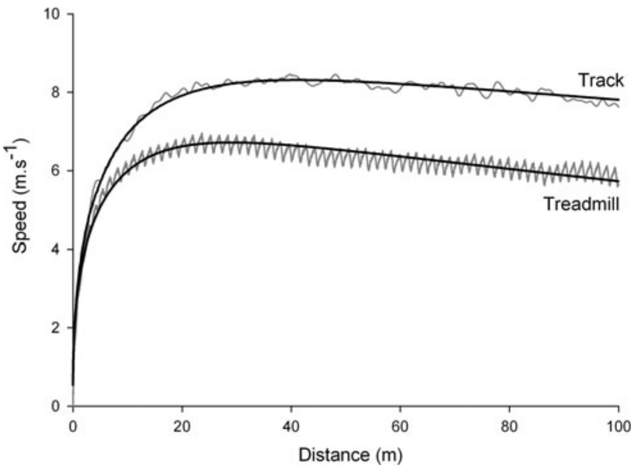

Fig. 4 Comparisons of distance-normalized typical instantaneous speed curves obtained in the typical subject mentioned in Fig. 1 on the track and on the treadmill. *Grey lines* are instantaneous velocities measured by the radar (track) and the treadmill. *Black lines* are the speed–distance curves predicted by the biexponential model described in Eq. 1

The performance variables put forward in our study clearly show an overall lower level of performance on the treadmill, by ~20% on average (Table 1), despite maximal effort made by subjects and "free" running made possible in both conditions. However, these variables (except tS_{max}) were all highly and significantly correlated between track and treadmill (Fig. 3). Such correlations had not been tested, to our knowledge in previous studies, except for S_{max} by Bundle et al. (Bundle et al. 2003), who showed a significant and high correlation, close to the line of identity (Fig. 4 in their study). Thus, we can reasonably state that when using a motorized treadmill (and setting a constant torque to overcome friction or at least limit its effects on speed), and allowing subjects to accelerate the belt voluntarily (i.e. without setting predetermined speed values), it is possible not to reproduce, but to interpret 100-m field sprint performance and investigate inter-subject differences. In other words, treadmill sprint performance is not equal to that observed in field conditions, but correlates significantly with it.

In this study, the motor torque was set to constantly assist subjects in their effort to accelerate the belt and maintain their speed (by overcoming the friction due to their body weight), and air friction was absent (contrary to field sprint). Thus, it seemed paradoxical to observe lower performances, though all the subjects performed all-out efforts and reported having had the feeling of maximal horizontal force production, very close to what they felt during field sprinting. This discrepancy was also intriguing since we observed the logical acceleration of the belt during aerial phases of the running steps. These phases lasted typically ~150–180 ms at high velocities, and the constant motor torque led to belt accelerations of about 2% of the belt speed at the moment of foot takeoff, on average for the entire group (data not presented). This change in belt speed during aerial phases is rather small (because of very short aerial phases during sprint running), but it may have been a reason for expecting higher S_{max} values compared to field conditions, since it occurs at each step.

Our most likely hypothesis to explain this difference in performance is that the characteristics of the treadmill, friction between the belt and the supporting frame during contact and vertical impulses, and overall inertia of the rollers–belt system limiting the speed production, are not fully overcome by the assisting motor torque. In an attempt (a) to estimate the difference in net horizontal force output between treadmill and field conditions and (b) investigate whether it was linked to subjects performance or mechanical output variables, we basically compared step-averaged values of Fh on the treadmill to estimated ones produced on the field at corresponding distances over the entire 100 m. When applying the fundamental law of dynamics in the horizontal direction (field data), the net force accelerating the body mass m (i.e. the force corresponding to Fh on the treadmill) may be computed as $F_{f\text{-}a} = ma$, with a the forward acceleration of the runner (in m s^{-2}) obtained from time derivation of modelled speed data. Since overcoming air friction may represent a source of force production in this direction in sprint running, we estimated the horizontal force produced against air friction as $F_{air} = ½.\rho\ A\ Cd\ S^2$ with ρ the air density (in kg m^{-3}), A the frontal area of the runner (in m^2), and Cd the drag coefficient. F_{air} was then estimated from this equation, subjects' body mass and height (used to compute A) and literature data, according to Arsac and Locatelli (2002). Then, the net horizontal force estimated on the field was computed as $Fh_{FIELD} = F_{f\text{-}a} + F_{air}$.

The typical comparison of Fh and Fh_{FIELD} during the 100 m (Fig. 5) shows the difference between track and treadmill. The data for the group show that this difference between Fh and Fh_{FIELD} was 79.7 ± 6.9 N on average (0.117 ± 0.009 times body weight) and significantly higher (t tests; $P < 0.001$) during the second part of the 100 m (i.e. after S_{max}), 86.7 ± 8.1 N than during acceleration (i.e. from start to S_{max}): 69.9 ± 8.5 N. Further, individual differences in net horizontal force between field and treadmill conditions computed over the 100-m sprint were significantly correlated with corresponding values of mean Fv per unit body weight ($r = 0.69$; $P = 0.023$), and not with subjects' body mass or treadmill Fh, S_{100}, S_{max}, Ph, t_a, t_c and f. These data clearly support the hypothesis that the difference in force production between the two situations is linked to mechanical variables representing the intensity of the vertical actions of subjects onto the belt during sprint, and thus to friction forces, since the friction

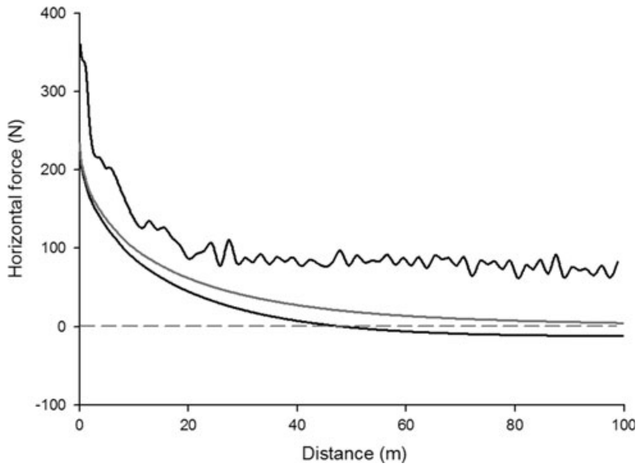

Fig. 5 Typical comparison between the step-averaged net horizontal force measured on the treadmill (spline curve between step-averaged values, upper trace) and that estimated from field instantaneous horizontal speed values (instantaneous values of modelled speed, black lower trace), and without taking account of the estimated horizontal force due to air friction (grey lower trace). For this typical subject (28 year-old athlete of 1.78 m, 71 kg), the mean difference in step-average value of propulsive force over the field 100 m was 84.3 ± 14.5 N, i.e. 0.128 ± 0.02 times the body weight

of the belt onto its supporting frame during contact is directly dependent on the amount of vertical force applied at the foot. This hypothesis was also proposed by Lakomy (1987) to explain the ~20% lower top speed reached on a non-motorized treadmill compared to the track condition: "The first major difference was due to the intrinsic resistance of the treadmill. This resistance, which was related to the weight of the runner, resulted in maximal velocities that were approximately 20% lower […]". The present study, though undertaken on a motorized treadmill, brings experimental evidences that support this hypothesis, with the novel point that the vertical force per unit body weight subjects apply onto the belt is related to this difference in performance, and that subjects' weight is not. Last, it is interesting to observe (Fig. 5) that on the treadmill, although maximal treadmill speed is reached, the step-averaged net horizontal force is still (a) positive, and (b) around 80 N in the typical example taken. This illustrates the fact that on the treadmill, subjects have to overcome an amount of force due to friction and/or inertia of the system, whereas on the track, maximal and then slightly decreasing speed are mechanically expected to be associated with approximately null and negative net horizontal forces, respectively.

Limits of the study

One of the limits of the present study is that a higher motor torque (i.e. 180 or 200% of the default value) could have been set, and thus could have allowed subjects to reach higher S_{max}. However, preliminary measurements (data not presented) performed on several subjects familiarized with the treadmill showed that even if S_{max} increased as the motor torque value increased, motor torques higher than the one used in the study (160% of the default torque) were too high to allow all the subjects to sprint comfortably (loss of balance, no upright position possible) and made them face a serious risk of fall.

Another limit is that this study investigated performance variables, which had, to our knowledge not been done to date, but the underlying mechanisms explaining the performances observed in both conditions are not known. If considered, as done in previous studies, they could help understand the origins of the field–treadmill differences put forward. Last, because the treadmill used in the present study was of a motorized type, this study could not test treadmill-field differences when a non-motorized treadmill is used, such as in previous studies (e.g. Lakomy 1987). Therefore, the present conclusions may be limited to motorized treadmills; the corresponding results for non-motorized treadmills remain unknown and are potential tracks of further research.

Conclusions

The motorized instrumented treadmill used allowed subjects to run in "free" running conditions, i.e. with no pre-determined speed belt, but the overall 100-m performances were lower than those observed during a field 100-m sprint. However, significant correlations were observed between field and treadmill performance variables, for instance for maximal and mean running speed. Therefore, it may be possible and useful to investigate sprint performance and mechanics on the treadmill, and possibly discuss inter-individual field sprint performance in light of treadmill measurements. From this comparison with field performance, it appears that the instrumented sprint treadmill could be a useful device to assess physical capacities of subjects involved in activities that include sprints (athletes, team sport players), and to monitor these capacities in the long term through a standardized follow-up. For instance, it could be used to follow and guide training programs aimed at improving mechanical power output during sprint running. Further, since the measurements of ground reaction force are made in both horizontal and vertical directions, an accurate assessment of the sprinting technique and the way subjects develop and apply force onto the ground is possible. Last, the instrumented treadmill used in this study could allow exploring running kinetics and kinematics over typical sprint distances (e.g. 50–400 m), including the acceleration phase, and not only over two or three steps at S_{max}. To our knowledge, this has never been done yet.

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Conflict of interest We declare that we have no conflict of interest.

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