



Effect of fatigue on force production and force application technique during repeated sprints

Jean-Benoit Morin ^{a,b,*}, Pierre Samozino ^{a,b}, Pascal Edouard ^{a,b}, Katja Tomazin ^{a,b,c}

^a University of Lyon, F-42023 Saint-Etienne, France

^b Laboratory of Exercise Physiology (EA4338), F-42000 Saint-Etienne, France

^c Faculty of Sport, University of Ljubljana, Ljubljana, Slovenia

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ABSTRACT

We investigated the changes in the technical ability of force application/orientation against the ground vs. the physical capability of total force production after a multiple-set repeated sprints series. Twelve male physical education students familiar with sprint running performed four sets of five 6-s sprints (24 s of passive rest between sprints, 3 min between sets). Sprints were performed from a standing start on an instrumented treadmill, allowing the computation of vertical (F_V), net horizontal (F_H) and total (F_{Tot}) ground reaction forces for each step. Furthermore, the ratio of forces was calculated as $RF = F_H F_{Tot}^{-1}$, and the index of force application technique (D_{RF}) representing the decrement in RF with increase in speed was computed as the slope of the linear RF -speed relationship. Changes between pre- (first two sprints) and post-fatigue (last two sprints) were tested using paired t -tests. Performance decreased significantly (e.g. top speed decreased by $15.7 \pm 5.4\%$; $P < 0.001$), and all the mechanical variables tested significantly changed. F_H showed the largest decrease, compared to F_V and F_{Tot} . D_{RF} significantly decreased ($P < 0.001$, effect size = 1.20), and the individual magnitudes of change of D_{RF} were significantly more important than those of F_{Tot} (19.2 ± 20.9 vs. $5.81 \pm 5.76\%$, respectively; $P < 0.01$). During a multiple-set repeated sprint series, both the total force production capability and the technical ability to apply force effectively against the ground are altered, the latter to a larger extent than the former.

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1. Introduction

Although top running speed and single all-out sprint effort are the basis of the main track and field event (100 m), the ability to repeat shorter sprints is of importance in many sports such as soccer or rugby. Therefore, repeated sprint ability (RSA) has been a recent area of investigations, and the focus of many studies in the past 15 years or so (for reviews, see [Glaister, 2005](#); [Spencer et al., 2005](#)), which almost exclusively focused on the physiological features of RSA, contributing to a detailed knowledge of this type of exercise. Comparatively, the biomechanical aspects of running RSA have almost never been explored.

Indeed, except for the mechanical output variables (typically work, velocity or power) measured as indicators of the performance decrement during cycling or running sprints series (e.g. [Balsom et al., 1994](#); [Gaitanos et al., 1993](#); [Hughes et al., 2006](#); [Mendez-Villanueva et al., 2008](#); [Serpiello et al., 2011](#); [Spencer et al., 2008](#)), no study

focused on how the orientation of the total force produced by lower limbs changes over a series of repeated sprints (RS). [Morin et al. \(2006\)](#) reported changes in running kinematics and spring-mass parameters over four consecutive field 100 m, but their field measurements at each step of the sprints did not include data of ground reaction forces (GRF) amplitude or orientation. More recently, [Girard et al. \(2011\)](#) reported changes in sprinting kinetics, kinematics and spring-mass characteristics over a series of 12 40 m sprints, and showed that positive peaks of horizontal GRF and horizontal positive and net impulses decreased, but peak vertical GRF did not change with fatigue. However, in their study, data were measured using a 5 m force plate yielding measurements of 2–4 steps in the 5–10 m (odd-numbered trials) or 30–35 m (even-numbered trials) consisting in sprinting back to the starting point) zones.

In contrast to this limited number of steps analyzed over each sprint, the recent validation of an instrumented sprint treadmill ([Morin et al., 2010](#)) makes continuous measurements of instantaneous horizontal and vertical GRF as well as the running speed (S) possible over an entire sprint, whatever its duration.

On the basis of these GRF measurements, we recently proposed the computation of the ratio of support-averaged net horizontal and vertical forces ($RF = F_H F_{Tot}^{-1}$) as an indicator of the

* Correspondence to: Laboratoire de Physiologie de l'Exercice (EA4338), Médecine du Sport—Myologie, CHU Bellevue, 42055 Saint-Etienne Cedex 2, France. Tel.: +33 477 120 734; fax: +33 477 127 229.

E-mail address: jean.benoit.morin@univ-st-etienne.fr (J.-B. Morin).

overall technical ability of force application and orientation against the ground, independently from the amount of total force applied (Morin et al., in press). Further, RF decreasing linearly with the increase in speed over a sprint acceleration from null to top speed, an index of force application technique (D_{RF}) was computed as the slope of the linear RF -speed relationship (Morin et al., in press). Thus for a given sprint, the higher D_{RF} , the more RF is maintained at high values despite increasing speed, and the more forward-oriented F_{Tot} . In turn, higher values of F_H are applied against the ground for a same given amount of F_{Tot} produced by the lower limbs. This D_{RF} index was highly and significantly correlated with field 100-m performance, while F_{Tot} computed over the entire acceleration phase was not (Morin et al., in press). Therefore, we proposed D_{RF} as an index of the overall force application technique during an accelerated run, in contrast to the amount of total force applied against the supporting ground F_{Tot} , which represents the overall physical capability of force production. In this study, it was shown that these two mechanical variables were not correlated, and that (at least for the population tested) the orientation of the total force applied against the ground at each step seemed more important than its amount.

The aim of the present study was therefore to compare the fatigue-induced changes in the technical ability of force application/orientation against the ground (especially represented by the D_{RF} index) to those in the physical capability of force production (especially the amount of total force applied against the ground per unit body weight (BW)). The physical capability of total force production was expected to decrease with fatigue and performance decrement induced by RS, and since force application technique has recently been related to single sprint performance (Morin et al., in press), we hypothesized that this variable would also decrease over a series of RS. The comparison of the respective extents of these decreases, if observed, was the main focus of this study.

2. Methods

2.1. Subjects and experimental protocol

Twelve male subjects (body mass (mean \pm SD) 75.1 ± 6.9 kg; height 1.80 ± 0.06 m; age 25.4 ± 4.1 years) volunteered to participate in this study. They were all physical education students and physically active, and had all practiced physical activities including sprints (e.g. soccer, basketball) in the 6 months preceding the study. 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.

About 1 week prior to the testing session, subjects undertook a complete familiarization session during which they repeated short (< 5 s) treadmill sprints at increasing intensities, with full recovery and until being comfortable with the running technique required (this took about 10 trials). Subjects then performed one maximal 6-s sprint, from which maximal power output was used as the criterion score for the first sprint of the RS series performed during the testing session. Indeed, to prevent pacing effects occurring in such RS protocols (Billaut et al., 2011), subjects were requested to achieve at least 95% of their respective criterion score during the first sprint of the RS testing session.

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. The RS protocol consisted of performing four sets of five 6-s sprints separated by 24 s of passive rest, with 3 min of recovery between sets. Subjects exercised to protocol completion or volitional fatigue, whichever occurred first.

The 6–24 s design was used to match the most common type of effort-rest durations in the literature (e.g. Edge et al., 2006). The multiple-set design was preferred to the commonly used single linear series of 5–20 sprints since it is more consistent with the typical effort of team sports during which sprint bouts are often clustered with short recovery during intense phases of the game, and these sprint sets are separated by longer recovery periods (Serpiello et al., 2011). Since the present study was part of a larger project, subjects performed the exact same succession of tasks (with the exact same time-distribution) during the 3 min recovery period between sets: one maximal squat jump, and two 5-s maximal

knee extensors isometric contractions during which neuromuscular measurements were performed (data not shown). Subjects were vigorously encouraged throughout RS.

2.2. Instrumented sprint treadmill

The motorized instrumented treadmill (ADAL3D-WR, Medical Development—HEF Tecmachine, Andrézieux-Bouthéon, France) used has recently been validated for sprint use (see Morin et al. 2010). It is mounted on a highly rigid metal frame fixed to the ground through four piezoelectric force transducers (KI 9077b, Kistler, Winterthur, Switzerland), and installed on a specially engineered concrete slab to ensure maximal rigidity of the supporting ground. The constant motor torque was set to 160% of the default torque, i.e. the motor torque necessary to overcome the friction on the belt due to subject's body weight. The default torque was measured by making the required subjects to stand still and by increasing the driving torque 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; Jaskolska et al., 1999; Morin et al., in press; Morin and Sève, in press), and with the detailed discussion by McKenna and Riches (2007). Motor torque of 160% of the default value was selected after several preliminary measurements comparing various torques, because it allowed subjects to sprint in a comfortable manner and produce maximal effort without risking the loss of balance. 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 with their preferred foot forward. This starting position was used and standardized all along the sprint series. After a 3-s countdown, the treadmill was released, and the belt began to accelerate as subjects applied a positive horizontal force.

2.3. Mechanical variables

Mechanical data were sampled at 1000 Hz continuously over the sprints, 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 data of vertical, net horizontal and total GRF were averaged for each support phase (vertical force above 30 N) over the 6-s sprints (F_V , F_H and F_{Tot} , respectively), and expressed in N and BW.

For each step, RF (in %) was calculated as the ratio of F_H to F_{Tot} for one contact period (Morin et al., in press). Then, mean and maximal values of RF for the 6-s sprint were computed (RF and RF_{max} , respectively). The index of force application technique (D_{RF}) representing the decrement in RF with the increasing speed was computed as the slope of the linear RF -speed relationship calculated from the step-averaged values between the second step and the step at top speed. Therefore, the higher the D_{RF} (i.e. a flat RF -speed relationship), the more RF is maintained despite increasing velocity, and vice versa. Last, for each 6-s sprint, performance was described through mean and maximal running speeds (S and S_{max} , respectively).

These data were completed by measurements of the main step kinematic variables: contact time (t_c in s), aerial time (t_a in s), step frequency (SF in Hz), step length (SL in m) and swing time (t_{swing}), i.e. the time to reposition the limb, from take-off to touch-down of the same foot.

2.4. Data analysis and statistics

Descriptive statistics are presented as mean values \pm SD. Normal distribution of the data was checked by the Shapiro–Wilk normality test, and the mechanical variables studied were compared between pre- and post-RS using t -test for paired samples. For each variable studied, pre- and post-values compared were the average data for the first two and last two sprints of each individual RS series, respectively. Furthermore, as recovery was expected to occur between sets, changes in performance, force production and force application technique were also studied within sprint sets (intra-set analysis), based on percent changes between the first and the last sprint of each set, and using t -test for paired samples. The importance of the differences found between pre- and post-RS was assessed through the effect size and Cohen's d coefficient (Cohen, 1988), interpreted as follows: small difference: $0.15 \leq d < 0.4$, medium difference: $0.40 \leq d < 0.75$, large difference: $0.75 \leq d < 1.10$ and very large difference: $d \geq 1.10$. The significance level was set at $P < 0.05$.

3. Results

Subjects performed (mean \pm SD) 16.7 ± 4.4 sprints. Among the 12 subjects, seven performed 20 sprints (4 sets), two performed 15 sprints (3 sets) and three completed 10 sprints (2 sets). Performance decreased significantly over the RS series, as shown in Table 1. This overall decrease was consistent with intra-set

Table 1

Changes in performance variables, force production and force application technique variables between the first two (pre-RS) and the last two (post-RS) sprints of the multiple-set repeated sprint series. All changes reported are significant.

	Pre-RS		Post-RS		t-Test P values	Pre-post % change		Effect size
S (m s^{-1})	4.55	(0.29)	3.83	(0.36)	< 0.001	–15.7	(5.4)	2.30 (very large)
$S\text{-max}$ (m s^{-1})	5.47	(0.40)	4.53	(0.42)	< 0.001	–17.2	(5.7)	2.39 (very large)
F_H (N)	309	(25)	267	(35)	< 0.001	–13.9	(8.5)	1.41 (very large)
F_H (BW)	0.416	(0.033)	0.359	(0.050)	< 0.001	–13.9	(8.5)	1.41 (very large)
F_V (N)	1074	(97)	1023	(103)	< 0.05	–5.12	(5.88)	0.66 (medium)
F_V (BW)	1.44	(0.10)	1.37	(0.12)	< 0.05	–5.12	(5.88)	0.66 (medium)
F_{Tot} (N)	1121	(99)	1060	(106)	< 0.001	–5.81	(5.76)	0.78 (large)
F_{Tot} (BW)	1.51	(0.11)	1.42	(0.13)	< 0.001	–5.81	(5.76)	0.78 (large)
RF (%)	27.7	(1.1)	25.6	(2.6)	< 0.001	–7.74	(8.13)	1.10 (very large)
$RF\text{-max}$ (%)	42.1	(2.6)	38.4	(3.2)	< 0.01	–8.41	(9.48)	1.33 (very large)
D_{RF}	–0.069	(0.007)	–0.081	(0.013)	< 0.001	–19.2	(20.9)	1.20 (very large)

Values are mean (SD).

Table 2

Intra-set percent changes in performance variables, force production and force application technique variables computed between the first and the last sprints of each set.

	Set #1 (n=12)		Set #2 (n=12)		Set #3 (n=9)		Set #4 (n=7)	
S (m s^{-1})	–8.54	(7.57)***	–10.8	(7.2)***	–10.8	(9.0)***	–5.49	(4.98)*
$S\text{-max}$ (m s^{-1})	–10.3	(3.6)***	–11.9	(7.7)***	–11.3	(6.6)***	–6.17	(6.5)*
F_H (BW)	–8.44	(7.56)***	–10.1	(9.1)*	–5.95	(5.90)*	–12.0	(11.5)*
F_V (BW)	–1.83	(3.66)	–6.46	(5.64)**	–6.94	(5.04)**	–5.63	(9.83)
F_{Tot} (BW)	–2.43	(3.40)*	–6.69	(4.87)***	–6.84	(4.68)**	–6.11	(9.79)
RF (%)	–5.53	(7.79)*	–3.77	(12.7)	1.80	(7.87)	–5.55	(7.59)
$RF\text{-max}$ (%)	–9.81	(8.05)**	–5.36	(17.7)	0.061	(12.7)	–2.18	(5.79)
D_{RF}	–4.49	(22.9)	–24.0	(29.0)*	–22.0	(32.6)	–16.7	(25.1)

Values are mean (SD).

* $P < 0.05$.

** $P < 0.01$.

*** $P < 0.001$.

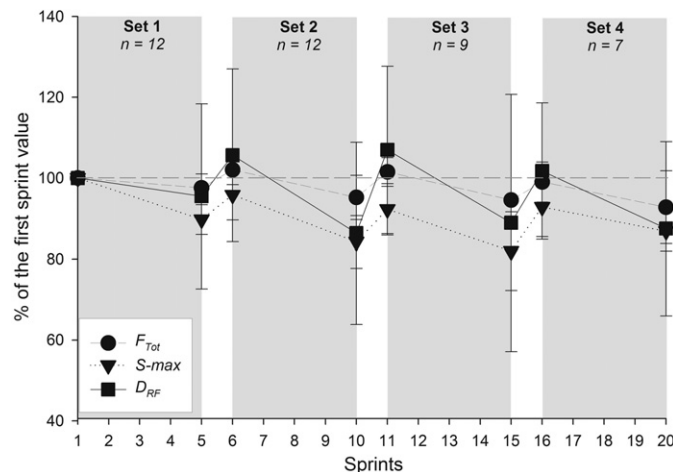


Fig. 1. Mean (\pm SD) changes in peak running speed, total force production and index of force application technique over the multiple-set sprint series. Values for the first and the last sprint of each set are expressed relatively to the value of the first sprint.

decreases in performance (Table 2). For instance, $S\text{-max}$ decreased by $\sim 8\text{--}10\%$ on an average over each of the four sets of 5 sprints (Table 2), for an overall mean decrease of $17.2 \pm 5.7\%$ ($P < 0.001$) between the first two and the last two sprints (Table 1). Within this overall inter- and intra-set decrease in performance, we observed that the level of performance was almost systematically higher at the beginning of sets #2, 3 and 4 than at the end of sets #1, 2 and 3 (Fig. 1). The 95% criterion score was overall satisfied: during the first sprint of the RS series, only one subject produced a mean power below 95% (94.3%) of that measured

during the first session of the protocol (mean \pm SD: $102 \pm 5.7\%$; range 94.3–112%).

All the mechanical variables tested significantly changed over the multiple-set RS series (Tables 1 and 3). F_H showed the largest decrease, compared to F_V and F_{Tot} . Furthermore, D_{RF} significantly decreased ($P < 0.001$, very large effect size), meaning that during each sprint the RF -speed relationship became steeper with fatigue (Fig. 2). In addition, all the individual RF -speed relationships were significantly linear (mean r^2 of 0.879; $P < 0.05$). Thus, as fatigue developed over the RS series, not only did subjects begin their sprints with a lower $RF\text{-max}$ value, but RF also decreased more rapidly (Table 1, Fig. 2). Finally, the individual magnitudes of change of D_{RF} were greater, and significantly more important than those of F_{Tot} (t -test; $P < 0.01$).

4. Discussion

The present results show that, along with the expected significant and large decrease in performance, RS induced both a significant decrease in the capability to produce total force and a significant and even larger decrease in the ability to apply it with a forward orientation during acceleration. The magnitude of these individual changes in D_{RF} was significantly ($P < 0.01$) larger than for F_{Tot} . Finally, this study reported similar ranges of decrease in performance than previous studies using linear RS series (e.g. Billaut and Basset, 2007; Bishop et al., 2001; Edge et al., 2006; Gaitanos et al., 1991, 1993; Girard et al., 2011; Hughes et al., 2006; Mendez-Villanueva et al., 2008) or a multiple-set RS design (Beckett et al., 2009; Serpiello et al., 2011).

To our knowledge, this is the first study reporting the effect of RS fatigue on force orientation technique, i.e. the ability to apply/orient

Table 3
Changes in running kinematics between the first two (pre-RS) and the last two (post-RS) sprints of the multiple-set repeated sprint series. All changes reported are significant.

	Pre-RS		Post-RS		t-Test P values	Pre-post % change		Effect size
t_c (s)	0.161	(0.012)	0.181	(0.021)	< 0.001	12.6	(10.1)	1.22 (very large)
t_a (s)	0.085	(0.011)	0.099	(0.009)	< 0.001	17.2	(15.1)	1.45 (very large)
t_{swing} (s)	0.328	(0.020)	0.375	(0.024)	< 0.001	14.5	(8.5)	2.22 (very large)
SF (Hz)	4.10	(0.21)	3.61	(0.26)	< 0.001	–11.9	(6.1)	2.17 (very large)
SL (m)	1.12	(0.10)	1.07	(0.08)	< 0.05	–4.03	(5.44)	0.58 (medium)

Values are mean (SD).

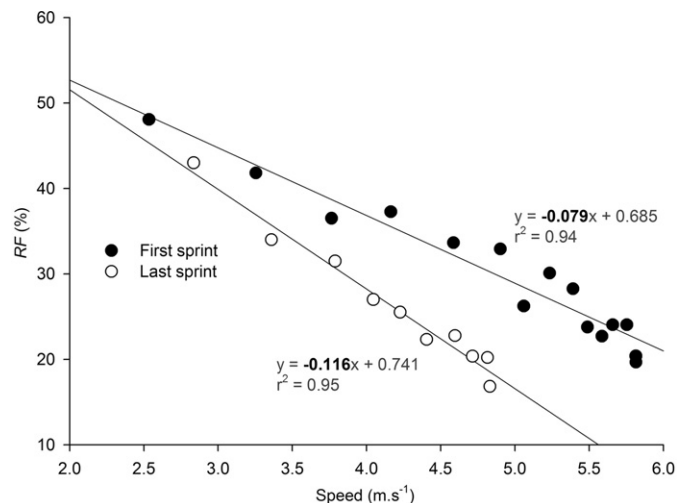


Fig. 2. Typical change in the RF -speed relationship between the first and the last sprints of the multiple-set sprint series (this typical subject completed the 4 sets of 5 sprints). D_{RF} values are computed as the slopes of these linear relationships (for this typical subject D_{RF} was equal to -0.079 and -0.116 for the first and the last sprints, respectively).

force effectively against the supporting ground. Though force production over RS has been approached in the previous works (Girard et al., 2011; Hughes et al., 2006), RF and D_{RF} variables had only been measured during single accelerations (Morin et al., in press). In the latter study, the authors showed that the variables characterizing the force application technique (RF and D_{RF}) were significantly related to field 100 m performance and that the main variable characterizing force production capability (F_{Tot}) was not. The present results show that the overall magnitude of performance decrease (i.e. $\sim 20\%$ on an average for the variables tested) could be related in large part to the technical ability of force application, since this change in performance was close to the change in D_{RF} . This index being computed as the slope of the linear decrease in RF with increasing speed, a decrease in the D_{RF} value means a faster straightening up of the total force vector during the acceleration from the start of the sprint (Fig. 2). Furthermore, a lower RF at the beginning of the acceleration (RF_{max}) was cumulated with a lower D_{RF} (i.e. a steeper slope of the RF -speed relationship), which led to shorter and less effective acceleration phases.

We observed that the above described decrease in F_{Tot} was accompanied by a very large decrease in F_H ($-13.9 \pm 8.5\%$; $P < 0.001$, effect size of 1.20), while F_V decreased significantly, but to a lesser extent ($-5.12 \pm 5.88\%$; $P < 0.05$, effect size of 0.66). This confirms that applying high amounts of F_H (in other words, orienting F_{Tot} forward) is determinant when trying to limit the decrease in performance during RS. This is in line with recent results of Kugler and Janshen (2010) who showed that the subjects applying more forward-oriented total force against the

ground (measured over one step) were performing better during a single sprint acceleration phase.

To our knowledge, only two studies described changes in sprint kinetics during RS (Girard et al., 2011; Hughes et al., 2006), yet with no focus on the force application/orientation technique. In a treadmill sprint reliability study, Hughes et al. (2006) reported horizontal force values (averaged over the entire 6-s sprint) and a mean percentage decrement of $\sim 7.5\%$ on an average across a series of 6 sprints. This is close to what we observed at the end of the first set of 5 sprints, and within each of the four sets of our study. Recently, Girard et al. (2011) published a detailed analysis of sprint kinematics and kinetics over a RS series of 12 40 m sprints performed overground. Though GRF measurements were only performed over 2–4 steps in the 5–10 m or 30–35 m intervals, fatigue-induced changes were reported: decrease in peak vertical GRF (though not significant, $P=0.17$), and significant decreases in both braking and pushing peaks of horizontal GRF. Though net horizontal force per step was not reported in their paper, it is likely that this variable (F_H in our study) decreased in their study.

Concerning running kinematics, Girard et al. (2011) observed a significant increase in t_c and t_a , and thus a decrease in SF . In their study, SL only tended ($P=0.06$) to increase. These changes in step kinematics and the absolute values reported were in line with the results of the present study: both SF and SL decreased significantly (Tables 3 and 4), but the latter significantly less than the former ($P < 0.05$). The decrease in SF was due to increases in t_c and t_a of very similar magnitudes ($12.6 \pm 10.1\%$, $P < 0.001$, effect size of 1.22, and $17.2 \pm 15.1\%$, $P < 0.001$, effect size of 1.45, respectively). These changes in t_a and t_c were not different ($P=0.40$), and the absolute values of t_a and t_c were in line with field and the sprint treadmill data reported for similar sprint speeds (e.g. Girard et al., 2011; Morin et al., in press; Weyand et al. 2000, 2010).

One limit of the present protocol is that the sprints were not performed overground. Though sprinting efforts would have been closer to the field performance, it would have made the continuous measurements of GRF impossible and thus running mechanics such as done here. This main drawback of the treadmill sprinting is outweighed by the possibility to comprehensively study sprinting mechanics. Furthermore, a recent study compared sprint performance on a 100 m between field and treadmill conditions (Morin and Sève, in press), using the same motorized treadmill as in the present study. Despite a difference in performance, the study reported high and significant correlations between the two conditions. Thus, it is reasonable to assume that the decrease in D_{RF} measured on the treadmill would also have occurred during such a multiple-set RS protocol performed on a standard track, and that the intra-individual changes observed would not have been fundamentally challenged. Finally, the values of mean and top speeds observed on the treadmill were ranging between those reported by Serpiello et al. (2011) (non-motorized treadmill, multiple-set RS study), and those reported by Girard et al. (2011) (field single-set RS study).

Table 4

Intra-set percent changes in running kinematics, computed between the first and the last sprints of each set.

	Set #1 (n=12)		Set #2 (n=12)		Set #3 (n=9)		Set #4 (n=7)	
tc (s)	12.2	(10.6)**	15.0	(12.6)**	14.1	(16.8)*	12.5	(10.9)*
ta (s)	−2.04	(18.3)	2.93	(20.5)	−2.37	(13.5)	−4.09	(11.3)
t _{swing} (s)	4.02	(7.43)	6.67	(6.59)**	4.59	(7.74)	1.96	(4.15)
SF(Hz)	−6.62	(3.90)***	−8.53	(3.51)***	−6.37	(7.45)*	−4.53	(3.10)**
SL (m)	−2.06	(3.25)*	−2.06	(7.22)	−4.68	(5.07)*	−1.71	(3.93)

Values are mean (SD).

* $P < 0.05$.** $P < 0.01$.*** $P < 0.001$.

In conclusion, both the total force production capability and the technical ability to apply/orient force effectively against the ground were altered during a multiple-set repeated sprint series, and the latter to a larger extent than the former. This study shows that running mechanics, especially the force production and the application technique, may bring additional insight to the extensively studied physiological features of repeated sprint performance. This could be of interest in sports where such maximal accelerations are frequently repeated over the game.

Conflict of interest

We declare that we have no conflict of interest.

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