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Running mechanical alterations during repeated treadmill sprints in hot *versus* hypoxic environments. A pilot study

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ABSTRACT

We determined if performance and mechanical running alterations during repeated treadmill sprinting differ between severely hot and hypoxic environments. Six male recreational sportsmen (team- and racket-sport background) performed five 5-s sprints with 25-s recovery on an instrumented treadmill, allowing the continuous (step-by-step) measurement of running kinetics/kinematics and spring-mass characteristics. These were randomly conducted in control (CON; 25°C/45% RH, inspired fraction of oxygen = 20.9%), hot (HOT; 38°C/21% RH, inspired fraction of oxygen = 20.9%; end-exercise core temperature: ~38.6°C) and normobaric hypoxic (HYP, 25°C/45% RH, inspired fraction of oxygen = 13.3%/simulated altitude of ~3600 m; end-exercise pulse oxygen saturation: ~84%) environments. Running distance was lower ($P < 0.05$) in HOT compared to CON and HYP for the first sprint but larger ($P < 0.05$) sprint decrement score occurred in HYP *versus* HOT and CON. Compared to CON, the cumulated distance covered over the five sprints was lower ($P < 0.01$) in HYP but not in HOT. Irrespective of the environmental condition, significant changes occurred from the first to the fifth sprint repetitions (all three conditions compounded) in selected running kinetics (mean horizontal forces, $P < 0.01$) or kinematics (contact and swing times, both $P < 0.001$; step frequency, $P < 0.001$) and spring-mass characteristics (vertical stiffness, $P < 0.001$; leg stiffness, $P < 0.01$). No significant interaction between sprint number and condition was found for any mechanical data. Preliminary evidence indicates that repeated-sprint ability is more impaired in hypoxia than in a hot environment, when compared to a control condition. However, as sprints are repeated, mechanical alterations appear not to be exacerbated in severe (heat, hypoxia) environmental conditions.

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KEYWORDS
Heat; hypoxia; repeated-sprint ability; sprinting mechanics

Introduction

Many sporting events are organized in hot environments (e.g., 2016 Olympic Games in Brazil) or at altitude (e.g., 2010 FIFA World Cup in South Africa), so the understanding of the impact of heat stress and hypoxia on in-competition physical performance is paramount. In team sports, both hot ambient conditions (i.e., environmental temperature >30°C) (Mohr & Krustrup, 2013; Mohr, Nybo, Grantham, & Racinais, 2012) and hypoxia (i.e., altitude >1500 m) (Garvican, Hammond, Varley, & Gore, 2014; Nassis, 2013) negatively alter match activity patterns. Reportedly, exertional heat stress elicits substantial decrements upon the completion of football-specific activities (i.e., jumps) (Mohr & Krustrup, 2013) and leads to pacing strategies (i.e., reduced amount of low-intensity running to preserve high-intensity actions) (Aughey, Goodman, & McKenna, 2014) due to increasing body temperatures, which would be pivotal to the outcome of a game. Likewise, with altitude ascent above sea level, lowered oxygen delivery to active tissues compromises aerobic capacity and inhibits recovery from high-intensity intermittent activity, thereby reducing the ability to sprint to the ball within a game (Aughey et al., 2013; Garvican et al., 2014).

Although there are compelling evidences to suggest that earlier and larger performance decrements occur when consecutive sprints (i.e., repeated-sprint ability) are undertaken with elevated heat stress (Drust, Rasmussen, Mohr, Nielsen, & Nybo, 2005; Girard, Brocherie, & Bishop, 2015) or limited oxygen availability (Billaut & Buchheit, 2013; Smith & Billaut, 2010), no direct (i.e., same participants) comparison exists for the effects of heat and hypoxia on repeated-sprint ability. Furthermore, while previous studies have mainly used cycle ergometry, the recent demonstration of exacerbated alterations in sprint capacity and resulting neuromuscular fatigue levels following cycling *versus* running repeated-sprint ability call into question the relevance of these findings in team sports (Rampinini et al., in press). The recent validation of an instrumented sprint treadmill (Morin, Samozino, Bonnefoy, Edouard, & Belli, 2010) made it possible to assess the instantaneous changes in both running velocity and ground reaction forces during maximal sprints similar to game play. For instance, Morin, Samozino, Edouard, and Tomazin (2011b) reported significant decrease

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in force production capacity and even larger deteriorations in the ability to apply forces horizontally during acceleration during repeated 6-s sprints. However, these observations have been made in cool/normoxic conditions.

The aim of the present study was to compare the performance changes and the accompanying alterations in running mechanics over a series of treadmill sprints performed in severely hot and hypoxic environments. While it was anticipated that, similar to control (e.g., cool, normoxic) condition (Morin et al., 2011b), the ability to apply/orient force would be more deteriorated than the total force production, we further hypothesised that heat stress and hypoxia would progressively exacerbate the magnitude of these alterations.

Methods

Participants

Six male recreational team- (football, rugby, basketball) or racket- (tennis, squash) sport players (34.0 ± 4.0 years; 178.1 ± 7.4 cm; 75.9 ± 9.7 kg; 2–4 h physical activity per week) participated in the study. Although residing in Qatar, the participants (all foreigners) were not accustomed to sprinting in the heat, as the study was conducted in the winter. They were all born and raised at <1500 m and had not travelled to elevations >1000 m in the 3 months prior to investigation. They gave their informed, written consent prior to the commencement of the experiment. Experimental protocol was conducted according to the Declaration of Helsinki and approved by the Ethics Committee of *Shafallah Medical Genetics Center*.

Experimental procedure

About 1 week prior to the first experimental session, participants undertook a familiarisation session consisting of short (<5 s) treadmill sprints at increasing intensities, with full recovery between each sprint. Sprints were repeated until participants felt comfortable with their running technique (i.e., 7–10 trials were generally needed). Afterwards, they performed three maximal 5-s single sprints separated by 2 min of passive rest, and the complete repeated-sprint ability test after 10 min of passive rest.

On three occasions, participants performed (in a counterbalanced randomised crossover design), at the same time of day (±1 h) and 4–5 days apart, five 5-s treadmill sprints with 25-s recovery. The trials were conducted in control (CON; 25°C/45% RH, inspired fraction of oxygen = 20.9%), hot (HOT; 38°C/21% RH, inspired fraction of oxygen = 20.9%) and normobaric hypoxic (HYP, 25°C/45% RH, inspired fraction of oxygen = 13.3%/simulated altitude of ~3600 m; Altitrainer, SMTEC SA, Nyon, Switzerland) environments with participants wearing similar sports gear (running shoes, short and T-shirt). These environmental conditions were chosen to reflect the extremes of heat (i.e., ambient temperature exceeding 35°C; Middle Eastern and Equatorial regions) and hypoxia (i.e., simulated altitude above 3000 m; mountainous regions of Pacific Latin America) that players may encounter during their practice. Our experimental conditions match field observations of football activity [i.e., decreases in total distance covered and at high-intensity (>14–15 km · h^{-1}) of ~7–8% and ~23–26%, respectively, compared to control] in either hot (43°C/12% RH) (Mohr et al., 2012) or hypoxic (natural altitude of 3600 m) (Aughey et al., 2013) conditions. Strong verbal encouragement was given during all maximal efforts. Participants were asked to avoid vigorous exercise and alcohol for 24 h, caffeine for 12 h and food for 2 h before all trials. They also kept a 24 h food diary prior to testing and replicated this diet before the three trials. During the period of testing, they were instructed to maintain their normal sleeping habits (>7 h/night) and normal diet (avoiding nutritional supplements). Participants were instructed to drink 4–6 mL of water per kilogram of body mass every 2.5 h on the day before each experimental session to ensure euhydration at the start of exercise; this has resulted in urine specific gravity (Pal-10-S, Vitech Scientific, West Sussex, UK) values of <1.015 g/mL before all trials. They were permitted to drink *ad libitum* during the warm-up procedure.

The repeated-sprint ability test was preceded by a warm-up consisting of 10 min of running at 10 km · h^{-1}, followed by 15 min of sprint-specific muscular warm-up exercises [i.e., 3 × (high knee, high heels, butt-kick, skipping for ~10 s with 30-s walking in between), followed by 3 × (three steps accelerations at a subjective "sense of effort" of 7, 8 and 9 on a modified Borg CR10 scale) (Christian, Bishop, Billaut, & Girard, 2014), then by 2 × (3-s sprints at a subjective "sense of effort" of 8 and 9 on the modified Borg CR10 scale], and finally three maximal 5-s sprints separated by 2 min of passive rest. In order to prevent any pacing strategy, the best sprint was used as the criterion score. The participants had to achieve at least 95% of the best trial during the first sprint of the repeated-sprint ability test, which was fulfilled in all of the three testing sessions. Participants were then allowed 5 min of free cool down prior to the repeated-sprint ability test. Duration of each trial (i.e., from the beginning of the warm-up until the end of the repeated-sprint ability test) was ~45 min.

Instrumented sprint treadmill

The sprints were performed on an instrumented motorised treadmill (ADAL3D-WR, Medical Development – HEF Tecmachine, Andrézieux-Bouthéon, France). For a detailed description of this device, see Morin et al. (2010); Morin, Edouard, and Samozino (2011a). Briefly, 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. This motorised treadmill allows participants to sprint and produce realistic acceleration and high running velocities (Morin et al., 2011a). A single-pass waist and a stiff rope (1 cm in diameter, ~2 m length) were used to tether participants to the 0.4-m vertical rail anchored to the wall behind them. When correctly attached, they were required to lean forward in a typical and standardised crouched sprint-start position with their left foot forward. Repeated-sprint ability was assessed from covered distance data using three scores: the largest (i.e., initial in all cases) distance ran, the cumulated distance covered over the five sprints (i.e., sum of the five sprints) and the sprint decrement score (Glaister, Howatson, Pattison, & McInnes, 2008).

Mechanical variables

Data were continuously sampled at 1000 Hz over the sprints, and after appropriate filtering (Butterworth-type 30 Hz low-pass filter; Adirun, Tecmachine, Andrézieux-Bouthéon, France), instantaneous data of vertical, net horizontal and total (i.e., resultant) ground reaction forces were averaged for each support phase (vertical force above 30 N) over the 5-s sprints, and expressed in body weight (BW). The index of force application technique representing the decrement in ratio of forces (ratio of forces = horizontal forces/total forces) with the increasing belt velocity ($m \cdot s^{-1}$) was computed as the slope of the linear ratio of forces-running velocity relationship calculated from the step-averaged values between the second step and the step at top running velocity (Morin et al., 2011a). These data were completed by measurements of the main step kinematic variables: contact time (s), aerial time (s), swing time (s), step frequency (Hz) and step length (m). Lastly, for each 5-s sprint, horizontal forces were used with the corresponding average belt velocity to compute net power output in the horizontal direction (propulsive power = horizontal forces × running velocity, $W \cdot kg^{-1}$). Each sprint trial included 15–18 ground contacts. After excluding the last two ground contacts, the remaining last three consecutive steps were used for the final analysis of sprint kinetics/kinematics (Brocherie, Millet, & Girard, 2015).

A linear spring-mass model of running (Butler, Crowell, & Davis, 2003; Coleman, Cannavan, Horne, & Blazevich, 2012; Morin, Dalleau, Kyröläinen, Jeannin, & Belli, 2005), applied in previous interventional [variations in running velocity (Arampatzis, Brüggemann, & Metzler, 1999) or repeated-sprint ability-fatigue (6 × 35 m with 10 s of active recovery: Brocherie et al., 2015; 12 × 40 m with 30 s of passive rest: Girard, Micallef, & Millet, 2011)] and reliability (Pappas, Paradisis, Tsolakis, Smirniotou, & Morin, 2014) studies, was used to investigate the main mechanical integrative parameters characterising the lower limb behaviour during running. Vertical stiffness ($kN \cdot m^{-1}$) was calculated as the ratio of peak vertical forces (N) to the maximal vertical downward displacement of centre of mass (m), which was determined by double integration of vertical acceleration of centre of mass over time during ground contact. Leg stiffness ($kN \cdot m^{-1}$) was calculated as the ratio of peak vertical forces to the maximum leg spring compression [maximal vertical downward displacement + L_0 $- \sqrt{L_0}^2 - (0.5 \times$ running velocity $\times$ contact time$)^2$, m], both occurring at mid-stance. Initial leg length (L_0, great trochanter to ground distance in a standing position) was determined from participant's stature as $L_0 = 0.53 \times$ stature (Morin et al., 2005).

Responses to exercise

Heart rate (all conditions), ratings of perceived exertion (all conditions) and pulse oxygen saturation (CON and HYP trials only) were monitored exactly 10 s following each sprint, respectively, via a wireless Polar monitoring system (Polar Electro Oy, Kempele, Finland), the Borg 6–20 scale and fingertip oximeter (Palmsat 2500, NONIN Medical Inc., Plymouth, MI, USA). Upon arrival on testing days (CON and HOT trials only), the telemetric temperature pill for monitoring core temperature (VitalSense®, Mini Mitter, Respironics, Herrsching, Germany) was inserted at the length distance of a gloved index finger beyond the anal sphincter. Skin temperatures of the chest, upper arm, thigh and lower leg were monitored via temperature data loggers (iButtons, Maxim Integrated, USA) and were used to calculate the mean skin temperature, using the equation of Ramanathan (1964).

Statistical analysis

Values are expressed as mean ± sd. Two-way repeated-measures analysis of variance (ANOVAs) [Time (Sprint number 1, 2, 3, 4 and 5) × Condition (CON, HOT and HYP)] was used to compare physiological/perceptual, running performance and mechanical responses. To assess assumptions of variance, Mauchly's test of sphericity was performed using all ANOVA results. A Greenhouse–Geisser correction was performed to adjust the degree of freedom if an assumption was violated, while a Bonferroni post hoc multiple comparison was performed if a significant main effect was observed. For each ANOVA, partial eta-squared was calculated as measures of effect size. Values of 0.01, 0.06 and values above 0.14 were considered as small, medium and large, respectively. All statistical calculations were performed using SPSS statistical software V.21.0 (IBM Corp., Armonk, NY, USA). The significance level was set at $P < 0.05$.

Results

Repeated-sprint ability

Distance ran during the first 5-s sprint was lower ($P < 0.05$) in HOT compared to CON and HYP (Table 1) but a larger ($P < 0.05$) sprint decrement score (7.9 ± 3.0% *vs.* 2.4 ± 3.4% and 3.1 ± 3.9%) occurred in HYP *versus* HOT and CON. Compared to CON (116.5 ± 6.3 m), the cumulated distance covered over the five sprints was shorter ($P < 0.01$) in HYP (110.5 ± 6.6 m) but not in HOT (112.1 ± 10.1 m), with no difference between HOT and HYP.

Responses to exercise

Heart rate (CON: 146 ± 14 bpm *vs.* 168 ± 10 bpm; HOT: 150 ± 11 bpm *vs.* 171 ± 8 bpm; HYP: 148 ± 23 bpm *vs.* 169 ± 15 bpm) and ratings of perceived exertion (CON: 12.3 ± 0.8 *vs.* 16.0 ± 1.6; HOT: 12.9 ± 0.2 *vs.* 17.1 ± 1.6; HYP: 12.0 ± 0.9 *vs.* 16.3 ± 1.3) increased from the first to the fifth repetitions ($P < 0.001$), irrespective of the environmental conditions, yet with higher ($P < 0.05$) ratings of

Table 1. Changes in performance, force production and application technique variables during the repeated-sprint ability test in control (CON), hot (HOT) and hypoxic (HYP) conditions.

		Sprint number							
	Condition	1	2	3	4	5	1–5 sprints average	1–5 sprints changes (%)	ANOVA main effects (Effect Sizes)
Distance covered (m)	**CON**	24.10 ± 1.97	23.58 ± 1.15	23.32 ± 1.05	22.93 ± 1.31*	22.53 ± 1.22*	**23.29 ± 1.26**	**−6.2 ± 4.9**	T < 0.001 (0.66)
	HOT	22.97 ± 1.97	22.45 ± 1.91	22.59 ± 2.36	22.42 ± 2.30*	21.62 ± 2.12*	**22.41 ± 2.02**	**−5.7 ± 7.2**	C = 0.088 (0.38)
	HYP	24.05 ± 2.15	22.03 ± 1.13	21.84 ± 0.83	21.35 ± 1.70*	21.27 ± 1.26*	**22.11 ± 1.33**	**−11.3 ± 4.6**	I = 0.004 (0.41)
Mean velocity (m · s^{-1})	**CON**	6.42 ± 0.34	6.20 ± 0.19	6.11 ± 0.23	6.02 ± 0.19*	5.91 ± 0.21*	**6.13 ± 0.19**	**−7.7 ± 5.2**	T < 0.001 (0.72)
	HOT	6.25 ± 0.51	6.08 ± 0.40	5.95 ± 0.40	5.84 ± 0.49*	5.68 ± 0.50*	**5.96 ± 0.42**	**−8.8 ± 8.0**	C = 0.176 (0.29)
	HYP	6.28 ± 0.34	5.93 ± 0.24	5.83 ± 0.23	5.71 ± 0.31*	5.63 ± 0.23*	**5.87 ± 0.24**	**−10.1 ± 4.6**	I = 0.339 (0.19)
Average vertical forces (Body weight)	**CON**	1.68 ± 0.34	1.67 ± 0.19	1.64 ± 0.23	1.67 ± 0.19	1.66 ± 0.21	**1.66 ± 0.06**	**−1.4 ± 5.2**	T < 0.252 (0.23)
	HOT	1.62 ± 0.34	1.63 ± 0.19	1.60 ± 0.23	1.58 ± 0.19	1.60 ± 0.21	**1.61 ± 0.06**	**−1.7 ± 8.0**	C = 0.242 (0.26)
	HYP	1.69 ± 0.34	1.65 ± 0.19	1.68 ± 0.23	1.67 ± 0.19	1.66 ± 0.21	**1.67 ± 0.10**	**−1.6 ± 4.6**	I = 0.416 (0.17)
Average horizontal forces (Body weight)	**CON**	0.22 ± 0.05	0.22 ± 0.05	0.20 ± 0.04	0.20 ± 0.04	0.20 ± 0.04*	**0.21 ± 0.04**	**−6.0 ± 12.2**	T < 0.006 (0.50)
	HOT	0.23 ± 0.03	0.23 ± 0.03	0.22 ± 0.03	0.20 ± 0.03	0.21 ± 0.04*	**0.22 ± 0.03**	**−9.7 ± 12.7**	C = 0.064 (0.42)
	HYP	0.20 ± 0.05	0.20 ± 0.06	0.19 ± 0.05	0.19 ± 0.05	0.18 ± 0.05*	**0.19 ± 0.05**	**−9.3 ± 17.0**	I = 0.867 (0.08)
Average total forces (Body weight)	**CON**	1.70 ± 0.07	1.68 ± 0.07	1.65 ± 0.05	1.68 ± 0.05	1.67 ± 0.07	**1.68 ± 0.06**	**−1.6 ± 3.7**	T < 0.171 (0.26)
	HOT	1.64 ± 0.06	1.64 ± 0.07	1.62 ± 0.09	1.59 ± 0.07	1.61 ± 0.07	**1.62 ± 0.06**	**−1.9 ± 3.5**	C = 0.247 (0.25)
	HYP	1.71 ± 0.12	1.67 ± 0.09	1.69 ± 0.10	1.68 ± 0.09	1.67 ± 0.10	**1.68 ± 0.10**	**−1.7 ± 3.8**	I = 0.352 (0.19)
Propulsive power (W · kg^{-1})	**CON**	13.77 ± 2.95	13.02 ± 2.41	11.71 ± 2.26	11.96 ± 2.43*	11.77 ± 2.24*	**12.45 ± 2.32**	**−13.2 ± 12.5**	T < 0.001 (0.68)
	HOT	14.05 ± 1.40	13.42 ± 0.99	12.51 ± 1.26	11.51 ± 1.57*	11.64 ± 2.72*	**12.63 ± 1.33**	**−17.0 ± 17.9**	C = 0.051 (0.45)
	HYP	11.22 ± 2.28	11.40 ± 3.05	10.75 ± 2.65	10.42 ± 2.76*	9.96 ± 2.26*	**10.95 ± 2.52**	**−18.4 ± 15.7**	I = 0.687 (0.68)
Index of force application technique	**CON**	−0.065 ± 0.008	−0.069 ± 0.011	−0.075 ± 0.009	−0.076 ± 0.013	−0.076 ± 0.008*	**−0.072 ± 0.009**	**17.1 ± 10.7**	T < 0.012 (0.60)
	HOT	−0.066 ± 0.010	−0.064 ± 0.011	−0.069 ± 0.012	−0.076 ± 0.011	−0.084 ± 0.025*	**−0.072 ± 0.013**	**25.6 ± 26.8**	C = 0.984 (0.03)
	HYP	−0.071 ± 0.011	−0.067 ± 0.020	−0.075 ± 0.019	−0.070 ± 0.013	−0.076 ± 0.023*	**−0.072 ± 0.016**	**6.6 ± 20.7**	I = 0.319 (0.19)

Notes: Values are mean ± SD. T, C, I – time, condition and interaction effects, respectively. *significantly different from sprint number 1 ($P < 0.05$).

perceived exertion values for the average of five sprints in the HOT trial (15.1 ± 1.2) compared to HYP (14.1 ± 1.2) and CON (14.1 ± 1.3). No statistically significant differences were found for the average of five sprints for core temperature between HOT and CON (38.57 ± 0.30°C *vs*. 38.50 ± 0.31°C), whereas skin temperature was elevated in the heat (37.33 ± 1.05°C *vs*. 33.26 ± 1.01°C; $P < 0.001$). Arterial oxygen saturation values decreased ($P < 0.001$) from the first to the last sprint in the HYP trial (88.8 ± 1.8 *vs*. 83.8 ± 4.8%), whereas it did not change in CON (97.3 ± 0.8 *vs*. 97.2 ± 1.7%).

Mechanical variables

Irrespective of the environmental condition, significant changes occurred from the first to the fifth repetitions in selected running kinetics (horizontal forces: −8.3 ± 10.3%, $P < 0.01$; Table 1) or kinematics (contact time and swing time: +12.2 ± 5.4% and +4.7 ± 4.4%, both $P < 0.001$; step frequency: −8.1 ± 3.2%, $P < 0.001$; Table 2) and spring-mass characteristics (peak vertical forces: −2.6 ± 2.4%, $P < 0.05$; maximal vertical downward displacement: +19.5 ± 8.3%, $P < 0.001$; leg compression: +7.3 ± 7.5%, $P < 0.05$; vertical stiffness: −17.8 ± 8.3%, $P < 0.001$; leg stiffness: −8.3 ± 5.8%, $P < 0.01$; Table 3). No significant interaction between time and conditions was found for any mechanical parameter.

Discussion

Repeated-sprint ability performance

Although exacerbated impairments in sprinting capacity in hot (Drust et al., 2005; Girard, Brocherie, et al., 2015) or hypoxic (Billaut & Buchheit, 2013; Smith & Billaut, 2010) *versus* cool or normoxic conditions have already been documented, sprint duration, type of recovery, number of sprint repetitions and training status of the participants all varied, which complicates comparisons of the extent of environmental-mediated fatigue-induced decrements in repeated-sprint ability between conditions. To our knowledge, the present study is

Table 2. Changes in running kinematics during the repeated-sprint ability test in control (CON), hot (HOT) and hypoxic (HYP) conditions.

		Sprint number							
	Condition	1	2	3	4	5	1–5 sprints average	1–5 sprints changes (%)	ANOVA main effects (Effect Sizes)
Contact time (s)	CON	0.141 ± 0.007	0.149 ± 0.007	0.156 ± 0.006*	0.154 ± 0.007*	0.157 ± 0.006*	**0.151 ± 0.005**	**11.6 ± 5.5**	T < 0.001 (0.83)
	HOT	0.147 ± 0.002	0.150 ± 0.005	0.156 ± 0.007*	0.161 ± 0.008*	0.167 ± 0.009*	**0.156 ± 0.005**	**13.2 ± 7.3**	C = 0.459 (0.12)
	HYP	0.145 ± 0.014	0.151 ± 0.016	0.157 ± 0.012*	0.160 ± 0.013*	0.161 ± 0.008*	**0.155 ± 0.013**	**11.7 ± 5.5**	I = 0.066 (0.29)
Aerial time (s)	CON	0.094 ± 0.016	0.095 ± 0.012	0.094 ± 0.008	0.096 ± 0.011	0.095 ± 0.010	**0.095 ± 0.011**	**2.2 ± 9.5**	T = 0.106 (0.30)
	HOT	0.087 ± 0.008	0.092 ± 0.012	0.091 ± 0.011	0.092 ± 0.009	0.093 ± 0.011	**0.091 ± 0.010**	**7.5 ± 6.5**	C = 0.477 (0.14)
	HYP	0.093 ± 0.010	0.095 ± 0.011	0.097 ± 0.009	0.097 ± 0.007	0.097 ± 0.010	**0.096 ± 0.009**	**4.3 ± 7.4**	I = 0.685 (0.12)
Swing time (s)	CON	0.324 ± 0.026	0.337 ± 0.026	0.345 ± 0.017*	0.343 ± 0.024*	0.347 ± 0.023*	**0.339 ± 0.022**	**7.2 ± 3.1**	T < 0.001 (0.79)
	HOT	0.319 ± 0.016	0.326 ± 0.030	0.337 ± 0.023*	0.340 ± 0.016*	0.350 ± 0.022*	**0.334 ± 0.022**	**9.9 ± 5.8**	C = 0.145 (0.32)
	HYP	0.329 ± 0.026	0.342 ± 0.030	0.350 ± 0.024*	0.354 ± 0.025*	0.354 ± 0.022*	**0.346 ± 0.025**	**7.8 ± 4.1**	I = 0.546 (0.15)
Step frequency (Hz)	CON	4.28 ± 0.29	4.12 ± 0.27*	4.02 ± 0.21*	4.03 ± 0.27*	3.98 ± 0.23*	**4.09 ± 0.25**	**−6.7 ± 3.9**	T < 0.001 (0.82)
	HOT	4.29 ± 0.17	4.15 ± 0.23*	4.05 ± 0.14*	3.97 ± 0.14*	3.86 ± 0.14*	**4.06 ± 0.15**	**−9.9 ± 3.3**	C = 0.457 (0.15)
	HYP	4.24 ± 0.32	4.10 ± 0.40*	3.96 ± 0.26*	3.92 ± 0.24*	3.90 ± 0.17*	**4.02 ± 0.27**	**−7.7 ± 4.5**	I = 0.206 (0.22)
Step length (m)	CON	1.54 ± 0.18	1.53 ± 0.13	1.53 ± 0.10	1.51 ± 0.13	1.50 ± 0.10	**1.53 ± 0.13**	**−2.2 ± 6.7**	T < 0.623 (0.12)
	HOT	1.48 ± 0.15	1.50 ± 0.17	1.50 ± 0.15	1.48 ± 0.21	1.48 ± 0.16	**1.49 ± 0.16**	**−0.3 ± 6.3**	C = 0.257 (0.25)
	HYP	1.53 ± 0.17	1.47 ± 0.16	1.48 ± 0.11	1.47 ± 0.12	1.46 ± 0.10	**1.48 ± 0.13**	**−4.0 ± 8.8**	I = 0.370 (0.18)

Notes: Values are mean ± SD. T, C, I – time, condition and interaction effects, respectively. *significantly different from sprint number 1 ($P < 0.05$).

Table 3. Changes in spring-mass characteristics during the repeated-sprint ability test in control (CON), hot (HOT) and hypoxic (HYP) conditions.

		Sprint number							
	Condition	1	2	3	4	5	1–5 sprints average	1–5 sprints changes (%)	ANOVA main effects (Effect Sizes)
Peak vertical forces (N)	CON	1973 ± 388	1922 ± 297	1879 ± 244	1904 ± 280	1889 ± 267*	**1914 ± 295**	**−3.5 ± 4.9**	T = 0.023 (0.42)
	HOT	1885 ± 281	1915 ± 306	1881 ± 297	1864 ± 257	1856 ± 307*	**1880 ± 288**	**−1.6 ± 3.6**	C = 0.798 (0.05)
	HYP	1919 ± 272	1903 ± 249	1887 ± 225	1870 ± 222	1865 ± 233*	**1889 ± 239**	**−2.6 ± 2.5**	I = 0.336 (0.19)
Centre of mass vertical displacement (m)	CON	0.027 ± 0.004	0.030 ± 0.004	0.031 ± 0.003*	0.031 ± 0.004*	0.032 ± 0.004*	**0.030 ± 0.003**	**+16.2 ± 9.1**	T < 0.001 (0.85)
	HOT	0.027 ± 0.002	0.029 ± 0.003	0.030 ± 0.002*	0.032 ± 0.002*	0.033 ± 0.003*	**0.030 ± 0.002**	**+23.5 ± 9.4**	C = 0.255 (0.24)
	HYP	0.028 ± 0.004	0.030 ± 0.005	0.032 ± 0.004*	0.033 ± 0.004*	0.033 ± 0.003*	**0.031 ± 0.004**	**+18.8 ± 11.6**	I = 0.253 (0.21)
Leg compression (m)	CON	0.144 ± 0.019	0.152 ± 0.020	0.162 ± 0.018	0.154 ± 0.017	0.154 ± 0.014*	**0.153 ± 0.016**	**+8.1 ± 10.2**	T = 0.034 (0.39)
	HOT	0.148 ± 0.024	0.149 ± 0.022	0.154 ± 0.019	0.158 ± 0.028	0.160 ± 0.018*	**0.154 ± 0.021**	**+9.2 ± 8.4**	C = 0.511 (0.13)
	HYP	0.146 ± 0.025	0.145 ± 0.029	0.152 ± 0.022	0.152 ± 0.022	0.150 ± 0.014*	**0.149 ± 0.022**	**+4.4 ± 11.4**	I = 0.439 (0.17)
Vertical stiffness ($kN \cdot m^{-1}$)	CON	72.4 ± 9.5	65.5 ± 7.8	60.7 ± 5.7*	62.1 ± 7.1*	60.1 ± 5.8*	**64.2 ± 6.9**	**−16.4 ± 6.4**	T < 0.001 (0.83)
	HOT	69.4 ± 7.3	65.9 ± 6.4	61.9 ± 6.4*	58.8 ± 5.2*	55.4 ± 5.8*	**62.3 ± 5.7**	**−19.9 ± 7.1**	C = 0.477 (0.14)
	HYP	69.4 ± 11.4	64.5 ± 11.9	59.3 ± 6.9*	57.8 ± 7.4*	56.8 ± 5.0*	**61.6 ± 8.2**	**−17.1 ± 8.1**	I = 0.160 (0.24)
Leg stiffness ($kN \cdot m^{-1}$)	CON	13.9 ± 2.7	12.8 ± 1.7	11.7 ± 0.6	12.5 ± 1.1*	12.3 ± 1.0*	**12.7 ± 1.3**	**−9.9 ± 10.1**	T = 0.007 (0.49)
	HOT	12.8 ± 1.2	13.1 ± 1.6	12.3 ± 1.5	11.9 ± 1.3*	11.6 ± 1.4*	**12.3 ± 1.1**	**−9.4 ± 8.2**	C = 0.655 (0.08)
	HYP	13.4 ± 2.5	13.5 ± 2.7	12.6 ± 1.5	12.5 ± 1.5*	12.5 ± 1.3*	**12.9 ± 1.8**	**−5.7 ± 9.4**	I = 0.408 (0.18)

Notes: Values are mean ± SD. T, C, I – time, condition and interaction effects, respectively. *significantly different from sprint number 1 ($P < 0.05$).

the first one where the same participants performed the same repeated-sprint ability test in control, hot and hypoxic conditions. Our data support that repeated-sprint ability is further compromised in HYP and to a lower extent in HOT (not statistically different), when directly compared to CON. Nevertheless, the “task-dependency” of the responses implies that heat stress and hypoxia could not be considered as “generic phenomena”. Hence, the type and the severity of each environmental stressor may well determine to which extent fatigue increases during each repeated-sprint ability test. For instance, large performance decrements solely occur in hotter conditions when consecutive sprints induce marked hyperthermia (core temperature >38.5°C) (Girard, Brocherie, et al., 2015). Compared to hot-dry environments, the ability of the body to extract heat through sweating is impaired in hot-humid conditions because sweat cannot readily evaporate off the body (Sawka, Leon, Montain, & Sonna, 2011), which will lead to greater hyperthermia and physiological strain and eventually larger impairment in repeated-sprint ability outcomes. Along the same lines, fatigue development during cycling repeated-sprint ability was exacerbated only under severe (inspired fraction of oxygen = 12–14%), but not moderate (inspired fraction of oxygen = 14–16%) hypoxic levels, when compared to normoxia (Bowtell, Cooke, Turner, Mileva, & Sumners, 2014; Goods, Dawson, Landers, Gore, & Peeling, 2014). As such, caution is needed when extrapolating our findings.

Physiological and perceptual responses

Larger repeated-sprint ability deterioration in HYP may relate to the decrease in convective factors of oxygen transport that occurred during the sprints, leading to a lower oxygen supply, as evidenced by the substantial hypoxemia level, with oxygenation saturation values below 85% at the end of exercise. Postulated mechanisms include a lower muscle reoxygenation capacity during recovery periods (Billaut & Buchheit, 2013) and/or a suboptimal muscle activation capacity stemming from lower oxygenation of the prefrontal cortex (Smith & Billaut, 2010). Furthermore, unchanged or enhanced short-term power output resulting from transient heat exposure, presumably attributable to improved muscle contractility, is a well-established finding (Girard, Brocherie, et al., 2015). In this study, the lack of difference between HOT and CON trials might arise from the narrow difference in core temperature (±0.10°C) and heart rate values. The fact that the participants also became “hyperthermic” in the CON trial (i.e., core temperature ≥38.5°C) indicates that the effect of the warm-up dominates over external heat in determining thermal strain. Interestingly though, our data indicate that for repeated-sprint efforts performed under severe heat stress, participants were able to overcome the thermal sensation linked to the environment (higher skin temperature and ratings of perceived exertion values) to maintain repeated-sprint ability close to CON conditions.

The development of hyperthermia and the concomitant rise in cardiovascular strain led to an increase in relative exercise intensity. Based on the rate of heat storage, it has also been proposed that muscle recruitment is adjusted or “down-regulated” in order to prevent thermal injury (Tucker, Rauch, Harley, & Noakes, 2004). During short repeated-sprint efforts pacing may occur, as it is influenced by manipulation of prior knowledge of sprint number (Billaut, Bishop, Schaerz, & Noakes, 2011). In the absence of surface EMG recording, it is difficult to accept or reject the hypothesis that the slowed sprints were due to a reduced neural drive. During hotter games, however, players apparently reduce the amount of low-intensity running to preserve high-intensity actions, while pacing strategies (i.e., influenced by tactics, opposition) during actual match play are difficult to predict (Aughey, Goodman, & McKenna, 2014). Furthermore, the direct effect of hypoxia in reducing the motor drive to the working muscles was shown to be only moderate at much higher altitude (inspired fraction of oxygen = 0.11) (Millet, Aubert, Favier, Busso, & Benoit, 2009), and it is therefore unlikely that this central regulation is paramount in the present study, where participants knew the number of sprint repetitions to be completed.

Sprint kinetics

In line with previous studies conducted in cool/normoxic conditions, our data showed that reductions in horizontal force production exceed those in the vertical direction in CON trial (Delextrat, Baliqi, & Clarke, 2013; Girard et al., 2011; Morin et al., 2011b). For example, the patterns and ranges of the present sprinting kinetics alterations mirror those previously reported (−1.8%, −8.4% and −2.4% for averaged vertical, horizontal and total forces, respectively) for the completion of five 6-s sprints with 24 s of rest (Morin et al., 2011b). A unique aspect of our study was that hot ambient and hypoxic conditions do not accentuate the extent of fatigue-induced changes in sprint kinetics. Disregarding the environmental conditions, our data confirm that producing large amounts of horizontal rather than large amounts of total forces to the ground is paramount to better preserve sprint capacity as fatigue develops (Morin et al., 2011b). Applying ground reaction impulse in a more horizontal direction is crucial for the ability to accelerate from a standing start, as it explains 44% and 61% of the variance of running speed at 8 m (Kawamori, Nosaka, & Newton, 2013) and 16 m (Hunter, Marshall, & McNair, 2005) from the start, respectively. Furthermore, the lower index of force application technique values (i.e., steeper slope of the ratio of forces-running velocity relationship) observed over the series indicates progressively shorter and less effective acceleration phases. However, with identical index of force application technique values (−0.072) for the five sprints across all three conditions, heat stress or hypoxia did not further deteriorate force application technique as participants became fatigued.

Sprint kinematics

The ability to tolerate impact/stretch loads progressively deteriorated across the five successive sprints. Specifically, substantial increases in contact and swing times occurred as fatigue developed, leading to a monotonic large decrease in step frequency, while flight time and step length were well preserved. Our results are in line with previous repeated-sprint ability studies, either on a treadmill (Delextrat et al., 2013; Morin et al., 2011a) or over the ground (Brocherie et al., 2015; Girard et al., 2011), with work-to-rest ratios ranging from 1:2 to 1:6. Moreover, the differences in performance between HYP and other trials seem too narrow for inducing large kinematic differences in stride efficiency. During a team-sport game, however, maximal efforts are often clustered with players performing multiple bouts of sprinting actions (Waldron & Highton, 2014). Conceivably, a single set repeated-sprint ability model may only poorly reflect the complex match activity patterns in team sports (Serpiello, McKenna, Stepto, Bishop, & Aughey, 2011). This implies that the above results would need to be confirmed under "real world settings" (Carling, 2013).

Spring-mass characteristics

Estimates of mechanical stiffness of the lower limbs are closely related to jumping and sprinting abilities, running economy as well as injury incidence (Butler et al., 2003). Across repetitions, without any influence of the environmental conditions, peak vertical forces decreased while both maximal vertical downward displacement and leg compression increased to a lower extent; this resulted in monotonic reductions in vertical stiffness, which are closely related to running velocity changes. While this corroborates previous field-based repeated-sprint ability conclusions (Brocherie et al., 2015; Girard et al., 2011), an interesting finding, however, is that leg stiffness followed a similar behaviour. Although Arampatzis et al. (1999) found that leg stiffness increases concomitantly with running velocity, fluctuations in leg stiffness values during field-based repeated-sprint ability tests have hitherto been reported as not significant despite profound slowing of running velocity in the most demanding protocols (Brocherie et al., 2015; Girard et al., 2011). In line with present results, however, a ~10% reduction in leg stiffness has been observed from the first to the fifth sprint repetitions when a larger cohort of athletes (n = 13) executed the same repeated-sprint ability test (Girard, Brocherie, Morin, Degache, & Millet, 2015). Further studies are needed to clarify this contention.

Limitations

The major weakness of this pilot study probably relates to the small number of participants involved. It is therefore likely that the statistical power of the current study may have been insufficient to identify meaningful differences linked to the environmental conditions *per se* in some of the mechanical variables, potentially due to large variability within and across days or a lower reliability in fatigued conditions. Of note, measurements of vertical stiffness and leg stiffness as well as related kinematic parameters (e.g., contact time, aerial time, step frequency and step length) when running for 30 s at a constant running velocity of 4.4 $m \cdot s^{-1}$ were found to be highly reliable (intraclass correlation coefficients ranging between 0.86 and 0.99) for both intra-day and inter-day designs (Pappas et al., 2014). More specifically, we have indicated that reliable running mechanical data can be derived from single 5-s sprints (three sprints separated by 2 min of passive recovery) on this instrumented treadmill on the same day and between days (5–7 days apart) (Girard, Brocherie, Morin, & Millet, in press). Reportedly, intra-session reliability was high (intraclass correlation coefficients >0.94 and coefficients of variation <8%) for performance outcomes (distance covered, mean velocity and propulsive power) and associated running mechanics. Furthermore, inter-session reliability was good for performance indices (0.83 < intraclass correlation coefficients < 0.89 and coefficients of variation < 10%) and high for kinetics (Intraclass correlation coefficients > 0.94 and coefficients of variation < 5%) and ranged between good and high for all kinematic (0.88 < intraclass correlation coefficients < 0.95 and coefficients of variation ≤ 3.5%) variables.

Although data were continuously collected, our analysis was based on averaging the representative steps near maximal running velocity for each 5-s sprint, which implies that interpretation of our results must remain specific to this phase of the sprint. Interestingly though, averaging data over "all steps" or only a few steps during early, middle or late phases of 5-s sprints provides similar mechanical outcomes during repeated treadmill sprinting (Girard, Brocherie, Morin, Degache, et al., 2015).

Finally, participants wore a facemask that was connected to the Altitrainer apparatus by a ~1.8-m long pipe during CON and HYP. An effect on performance induced by mask breathing *per se* during testing is unlikely, since its resistance and increase in dead space is negligible (i.e., no additional specific work of the respiratory muscles) compared to "normal breathing" (Sheel, 2002). In these conditions, we assumed that the influence of mask breathing on our observed repeated-sprint ability outcomes is likely to be negligible and therefore did not modify the main findings of this study.

Conclusion

This study was designed to directly compare the magnitude of the running performance and mechanical alterations during repeated treadmill sprinting in severe heat and hypoxic conditions. Preliminary evidence indicates that repeated-sprint ability is more impaired in hypoxia than in hot environment when compared to a control condition. However, the nature and extent of fatigue-induced alterations in running kinetics, kinematics and spring-mass characteristics did not differ between the three environmental conditions. Despite this, there is a possibility (yet unknown) that other specific phases of the sprint (e.g., early acceleration, deceleration phases) would be more sensitive to heat stress or hypoxia, but this needs to be further investigated. Specific strategies, including heat acclimation protocols, mixed methods of cooling and/or maintenance of hydration status, have proven to be efficient at mitigating heat-related decrements in repeated-sprint performance (Girard, Brocherie, et al., 2015), while tolerance for exercise of this nature is also improved with altitude training/acclimatisation (Girard et al., 2013). How this potential environmentally mediated improvement in repeated-sprint ability would also lead to biomechanical adaptations still needs to be thoroughly documented.

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Disclosure statement

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References

Arampatzis, A., Brüggemann, G.-P., & Metzler, V. (1999). The effect of speed on leg stiffness and joint kinetics in human running. *Journal of Biomechanics*, *32*(12), 1349–1353.

Aughey, R. J., Goodman, C. A., & McKenna, M. J. (2014). Greater chance of high core temperatures with modified pacing strategy during team sport in the heat. *Journal of Science and Medicine in Sport*, *17*(1), 113–118.

Aughey, R. J., Hammond, K., Varley, M. C., Schmidt, W. F., Bourdon, P. C., Buchheit, M., & Gore, C. J. (2013). Soccer activity profile of altitude versus sea-level natives during acclimatization to 3600 m (ISA3600). *British Journal of Sports Medicine*, *47*(1), i107–i113.

Billaut, F., Bishop, D. J., Schaerz, S., & Noakes, T. D. (2011). Influence of knowledge of sprint number on pacing during repeated-sprint exercise. *Medicine & Science in Sports & Exercise*, *43*(4), 665–672.

Billaut, F., & Buchheit, M. (2013). Repeated-sprint performance and vastus lateralis oxygenation: Effect of limited O_2 availability. *Scandinavian Journal of Medicine and Science in Sports*, *23*(3), 185–193.

Bowtell, J. L., Cooke, K., Turner, R., Mileva, K. N., & Sumners, D. P. (2014). Acute physiological and performance responses to repeated sprints in varying degrees of hypoxia. *Journal of Science and Medicine in Sport*, *17*(4), 399–403.

Brocherie, F., Millet, G. P., & Girard, O. (2015). Neuro-mechanical and metabolic adjustments to the repeated anaerobic sprint test in professional football players. *European Journal of Applied Physiology*, *115*(5), 891–903.

Butler, R. J., Crowell, H. P., & Davis, I. M. (2003). Lower extremity stiffness: Implications for performance and injury. *Clinical Biomechanics*, *18*(6), 511–517.

Carling, C. (2013). Interpreting physical performance in professional soccer match-play: Should we be more pragmatic in our approach? *Sports Medicine*, *43*(8), 655–663.

Christian, R. J., Bishop, D. J., Billaut, F., & Girard, O. (2014). The role of sense of effort on self-selected cycling power output. *Frontiers in Physiology*, *5*, 115.

Coleman, D. R., Cannavan, D., Horne, S., & Blazevich, A. J. (2012). Leg stiffness in human running: Comparison of estimates derived from previously published models to direct kinematic-kinetic measures. *Journal of Biomechanics*, *45*(11), 1987–1991.

Delextrat, A., Baliqi, F., & Clarke, N. (2013). Repeated sprint ability and stride kinematics are altered following an official match in national-level basketball players. *Journal of Sports Medicine and Physical Fitness*, *53*(2), 112–118.

Drust, B., Rasmussen, P., Mohr, M., Nielsen, B., & Nybo, L. (2005). Elevations in core and muscle temperature impairs repeated sprint performance. *Acta Physiologica Scandinavica*, *183*(2), 181–190.

Garvican, L. A., Hammond, K., Varley, M. C., Gore, C. J., Billaut, F., & Aughey, R. J. (2014). Lower running performance and exacerbated fatigue in soccer played at 1600 m. *International Journal of Sports Physiology and Performance*, *9*(3), 397–404.

Girard, O., Amann, M., Aughey, R. J., Billaut, F., Bishop, D. J., Bourdon, P., & Schumacher, Y. O. (2013). Position statement – altitude training for improving team-sport players' performance: Current knowledge and unresolved issues. *British Journal of Sports Medicine*, *47*(1), i8–i16.

Girard, O., Brocherie, F., & Bishop, D. J. (2015). Sprint performance under heat stress: A review. *Scandinavian Journal of Medicine and Science in Sports*, *25*(1), 79–89.

Girard, O., Brocherie, F., Morin, J. B., Degache, F., & Millet, G. P. (2015). Comparison of four sections for analyzing running mechanics alterations during repeated treadmill sprints. *Journal of Applied Biomechanics*. doi.10.1123/jab.2015-0049

Girard, O., Brocherie, F., Morin, J.-B., & Millet, G. P. (in press). Intra- and inter-session reliability of running mechanics during treadmill sprints. *International Journal of Sports Physiology and Performance*. http://dx.doi.org/10.1123/ijspp.2015-0145

Girard, O., Micallef, J.-P., & Millet, G. P. (2011). Changes in spring–mass model characteristics during repeated running sprints. *European Journal of Applied Physiology*, *111*(1), 125–134.

Glaister, M., Howatson, G., Pattison, J. R., & McInnes, G. (2008). The reliability and validity of fatigue measures during multiple-sprint work: An issue revisited. *Journal of Strength and Conditioning Research*, *22*(5), 1597–1601.

Goods, P. S. R., Dawson, B. T., Landers, G. J., Gore, C. J., & Peeling, P. (2014). Effect of different simulated altitudes on repeat-sprint performance in team-sport athletes. *International Journal of Sports Physiology and Performance*, *9*(5), 857–862.

Hunter, J. P., Marshall, R. N., & McNair, P. J. (2005). Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *Journal of Applied Biomechanics*, *21*(1), 31–43.

Kawamori, N., Nosaka, K., & Newton, R. U. (2013). Relationships between ground reaction impulse and sprint acceleration performance in team sport athletes. *Journal of Strength and Conditioning Research*, *27*(3), 568–573.

Millet, G. Y., Aubert, D., Favier, F. B., Busso, T., & Benoit, H. (2009). Effect of acute hypoxia on central fatigue during repeated isometric leg contractions. *Scandinavian Journal of Medicine and Sciences in Sports*, *19*(5), 695–702.

Mohr, M., & Krustrup, P. (2013). Heat stress impairs repeated jump ability after competitive elite soccer games. *Journal of Strength and Conditioning Research*, *27*(3), 683–689.

Mohr, M., Nybo, L., Grantham, J., & Racinais, S. (2012). Physiological responses and physical performance during football in the heat. *PLoS One*, *7*(6), e39202.

Morin, J.-B., Dalleau, G., Kyrölainen, H., Jeannin, T., & Belli, A. (2005). A simple method for measuring stiffness during running. *Journal of Applied Biomechanics*, *21*(2), 167–180.

Morin, J.-B., Edouard, P., & Samozino, P. (2011a). Technical ability of force application as a determinant factor of sprint performance. *Medicine & Science in Sports & Exercise*, *43*(9), 1680–1688.

Morin, J. B., Samozino, P., Bonnefoy, R., Edouard, P., & Belli, A. (2010). Direct measurement of power during one single sprint on treadmill. *Journal of Biomechanics*, *43*(10), 1970–1975.

Morin, J.-B., Samozino, P., Edouard, P., & Tomazin, K. (2011b). Effect of fatigue on force production and force application technique during repeated sprints. *Journal of Biomechanics*, *44*(15), 2719–2723.

Nassis, G. P. (2013). Effect of altitude on football performance: Analysis of the 2010 FIFA world cup data. *Journal of Strength and Conditioning Research*, *27*(3), 703–707.

Pappas, P., Paradisis, G., Tsolakis, C., Smirniotou, A., & Morin, J.-B. (2014). Reliabilities of leg and vertical stiffness during treadmill running. *Sports Biomechanics*, *13*(4), 391–399.

Ramanathan, N. L. (1964). A new weighting system for mean surface temperature of the human body. *Journal of Applied Physiology*, *19*(3), 531–533.

Rampinini, E., Connolly, D. R., Ferioli, D., La Torre, A., Alberti, G., & Bosio, A. (in press). Peripheral neuromuscular fatigue induced during by repeated-sprint exercise: Cycling *vs* running. *Journal of Sports Medicine and Physical Fitness*. doi:10.1123/ijspp.2015-0145

Sawka, M., Leon, L. R., Montain, S. J., & Sonna, L. A. (2011). Integrated physiological mechanisms of exercise performance, adaptation, and maladaptation to heat stress. *Comprehensive Physiology*, *1*(4), 1883–1928.

Serpiello, F. R., McKenna, M. J., Stepto, N. K., Bishop, D. J., & Aughey, R. J. (2011). Performance and physiological responses to repeated-sprint exercise: A novel multiple-set approach. *European Journal of Applied Physiology*, *111*(4), 669–678.

Sheel, A. W. (2002). Respiratory muscle training in healthy individuals: Physiological rationale and implications for exercise performance. *Sports Medicine*, *32*(9), 567–581.

Smith, K. J., & Billaut, F. (2010). Influence of cerebral and muscle oxygenation on repeated-sprint ability. *European Journal of Applied Physiology*, *109*(5), 989–999.

Tucker, R., Rauch, L., Harley, Y. R., & Noakes, T. D. (2004). Impaired exercise performance in the heat is associated with an anticipatory reduction in skeletal muscle recruitment. *Pflugers Arch*, *448*(4), 422–430.

Waldron, M., & Highton, J. (2014). Fatigue and pacing in high-intensity intermittent team sport: An update. *Sports Medicine*, *44*(12), 1645–1658.