



Original research

Heat stress impairs proprioception but not running mechanics

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ARTICLE INFO

Article history:

Received 24 April 2019

Received in revised form 14 July 2019

Accepted 19 July 2019

Available online 24 July 2019

Keywords:

Self-paced exercise

Sense of position

Kinetics

Kinematics

Hyperthermia

ABSTRACT

Objectives: To determine the effects of heat stress on ankle proprioception and running gait pattern.

Design: Counterbalanced repeated measures.

Methods: 12 trained runners performed a proprioception test (active movement discrimination) before and immediately after a 30 min, self-paced treadmill run in HOT (39°C) and COOL (22°C) ambient conditions. Velocity was imposed during the first and last minute (70% of maximal aerobic velocity, $13.3 \pm 0.8 \text{ km h}^{-1}$) for determination of running mechanics and spring–mass characteristics.

Results: Rectal (39.7 ± 0.4 vs. 39.4 ± 0.4 °C), skin (36.3 ± 1.1 vs. 31.8 ± 1.1 °C) and average body (38.3 ± 0.2 vs. 36.4 ± 0.4 °C) temperatures together with heart rate (178 ± 8 vs. 174 ± 6 bpm) and thermal discomfort (6.5 ± 0.5 vs. 4.3 ± 1.3) were all higher at the end of the HOT compared to COOL run (all $p < 0.05$). Distance covered was lower in HOT than COOL ($-5.1 \pm 3.6\%$, $p < 0.001$). Average error during the proprioception test increased after running in HOT ($+11\%$, $p < 0.05$) but not in COOL (-2%). There was no significant difference for most segmental and joint angles at heel contact, except for a global increase in pelvis retroversion and decrease in ankle dorsi-flexion angles with time ($p < 0.05$). Step frequency decreased ($-2.5 \pm 3.6\%$) and step length increased ($+2.6 \pm 3.8\%$) over time ($p < 0.05$), independently of condition. Spring–mass characteristics remained unchanged (all $p > 0.05$).

Conclusions: Heat stress exacerbates thermal, cardiovascular and perceptual responses, while running velocity was slower during a 30 min self-paced treadmill run. Heat stress also impairs ankle proprioception during an active movement discrimination task, but it has no influence on gait pattern assessed at a constant, sub-maximal velocity.

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Practical implications

- Heat stress impairs ankle proprioceptive acuity.
- Heat-induced deterioration of ankle proprioception does not affect treadmill running mechanics at a given velocity.
- Heat stress does not affect running mechanics at moderate constant velocity treadmill run.

1. Introduction

When exercising in hot environments, the impairment of heat loss capacities creates major thermal and cardiovascular

challenges,¹ progressively lowering power output or velocity during self-paced cycling¹ or running.² Moreover, passive hyperthermia impairs various indices of balance and ankle proprioception,³ and one can argue that perturbations in proprioception may increase injury risk⁴ and hamper running performance.⁵ In that regard, the ankle–foot complex is particularly important as it represents the only connection of the body with the ground. Han et al.⁶ measured ankle proprioception of 100 elite athletes and found that ankle proprioception scores could predict performance level across five different sports. Among other joints, ankle proprioception also displayed the strongest association with performance level.⁷ This raises the question of the effect of the impairment in ankle proprioception recently reported during passive hyperthermia³ on running kinematics in hot ambient conditions.

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Running has often been described as a locomotion similar to bouncing, in which the running leg functions as a linear spring loaded by the weight and inertia of the body mass.⁸ This paradigm refers to the “spring–mass model” and is commonly applied during constant-velocity runs in normothermic conditions.⁹ In the only heat-related study, longer contact time along with lower step frequency and vertical stiffness developed when sprinting repeatedly in hot conditions, while stride mechanical pattern remained unchanged from pre to post repeated sprints at low and high constant velocities.¹⁰

The aim of this study was to determine the effect of exercise-induced heat stress on ankle proprioception and any potential consequences on running mechanics. We hypothesized that exercise-induced heat stress would impair ankle proprioception, in turn altering foot strike pattern as manifested by kinematic and spring–mass model adjustments.

2. Methods

The project was approved by Aspetar Scientific Committee (CMO/0000115/fj) and by an External Ethics Committee (Anti-Doping Laboratory Qatar, E2016000127). The procedures complied with the *Declaration of Helsinki* regarding human experimentation. Written informed consent was obtained from all participants.

From an initial sample size of 18 participants, four did not satisfy the selection criteria of a maximal aerobic velocity (MAV) $\geq 18 \text{ km h}^{-1}$ and two dropped out for medical reason. Participants (11 males, 1 female) were non-heat-acclimated trained runners (age: 33.7 ± 5.6 yrs; body mass: 74.3 ± 6.8 kg; height: 177.3 ± 6.7 cm; average MAV: $19 \pm 1.1 \text{ km h}^{-1}$, range $18.0\text{--}21.3 \text{ km h}^{-1}$). All participants self-reported to be healthy, not under current medication and free of any lower-limb injury for at least two years before the study. Participants were instructed to avoid vigorous activity for the 24 h preceding each trial.

Approximately one week prior to testing, participants completed a pre-experimental session in cool conditions. First, participants were fully familiarized with the proprioception test. Afterwards, they performed an incremental test including four 4 min stages (8.5 km h^{-1} , 10 km h^{-1} , 11.5 km h^{-1} and 13 km h^{-1}) followed by increases of 1 km h^{-1} every minute until exhaustion in order to estimate MAV. Finally, they completed 10 min of self-paced run.

Participants performed two experimental sessions, one in COOL (22°C , 48% RH) and one in HOT (39°C , 21% RH) ambient conditions. Participants emptied their bladder upon arrival to the laboratory and provided a urine sample for the measurement of urine specific gravity (USG) (URC-NE; Atago, Tokyo, Japan). If the USG was >1.020 , the trial was postponed to allow the participants to drink more water. They were weighed nude before changing into running attire, self-inserting a rectal telemetric thermistor and being instrumented with a heart rate monitor, skin temperature sensors and reflective markers (see below). Afterward, they performed a proprioception test followed by a self-paced treadmill run then immediately another proprioception test. The environmental temperature during the HOT sessions was controlled by 9 heaters (Black&Decker HX280-B5, Maryland, USA) placed all around the treadmill. Upon finishing all the testing, participants were weighed again nude and dry. All trials were performed at the same time of day (± 1 h) in a counterbalanced order, 4–7 days apart with participants wearing the same attire (shoes and tight shorts only).

Proprioception was evaluated using a purpose-built Active Movement Extent Discrimination Apparatus (AMEDA) to assess dorsiflexion discrimination acuity. The equipment and procedure were similar to previously reported.³ Briefly, participants stood upright with the left foot on a fixed platform and the right foot

on a mobile platform allowing free dorsiflexion until a stopper randomly set to one of the five possible positions (i.e. dorsiflexion of 11.2 , 11.9 , 12.6 , 13.3 or 14.0 degrees, Fig. 1). Following 15 trials for familiarization, the test consisted in 50 trials in a random sequence for which participants estimated the position number (1–5). The complete test took 7 ± 0.1 min and was performed in the beside the treadmill, in the selected environment (i.e. COOL or HOT). The mean error was computed.³

The runs started by 10 min of standardized warm-up followed by 5 min of recovery before the 30 min self-paced run. The first (Onset) and last (Endpoint) minutes of the run were performed at an imposed velocity corresponding to 70% of MAV (average $13 \pm 0.8 \text{ km h}^{-1}$, range $12.6\text{--}14.9 \text{ km h}^{-1}$) to allow comparison of the running mechanics at a similar velocity between (COOL vs. HOT) and within (onset vs. endpoint) conditions. Participants were instructed to cover the most distance possible during the 28 min remaining. A timer-screen was placed right in front of the runners to keep them continuously informed about the running time. The same experimenter had the control over the treadmill which was already set at the specific imposed speed of each participant before starting the test and was in charge of adapting the velocity with a precision of 0.1 km h^{-1} at any time upon the participant's request. Testing procedures were the same in COOL and HOT and participants were allowed to drink ad libitum.

Rectal temperature (Tcore) was monitored via a telemetric temperature pill (EQ-ACC-023, Equivital, UK) self-inserted by the length of a gloved index finger beyond the anal sphincter. Skin temperatures of the upper arm, thigh and lower leg were monitored via data loggers (iButton, Maxim Integrated Products, USA), chest temperature was monitored via a chest strap (EQ02, Equivital, UK). Mean skin temperature (Tskin) was calculated as $0.3 \times \text{chest} + 0.3 \times \text{upper arm} + 0.2 \times \text{thigh} + 0.2 \times \text{lower leg}$.¹¹ Whole body temperature (Tbody) was calculated as $0.66 \times \text{Tcore} + 0.34 \times \text{Tskin}$ in COOL, and $0.79 \times \text{Tcore} + 0.21 \times \text{Tskin}$ in HOT.¹² Heart rate (HR) was monitored with a Polar transmitter-receiver (T-31; Polar Electro, Lake Success, NY, USA). Thermoregulatory and HR data were continuously collected during all the testing.

Thermal comfort (TC) scores were recorded using a seven-point scale with 1 representing ‘too cool’ and 7 ‘much too warm’ situations.¹³ Ratings of perceived exertion (RPE) were recorded using a 6–20 scale.¹⁴ Perceptual data were collected prior and after the proprioceptive testing and at 5 min intervals during the 30 min self-paced running.

Participants ran on an instrumented treadmill (ADAL3D-WR, Medical Development–HEF Tecmachine, Andrezieux-Boutheon, France) mounted on a highly rigid metal frame fixed to the ground through four piezoelectric force transducers (KI 9077b; Kistler, Winterthur, Switzerland). The treadmill was installed on a specially engineered concrete slab to ensure maximal rigidity of the supporting ground. Data were sampled at 1000 Hz. After appropriate filtering (Butterworth-type, 30 Hz low-pass filter), instantaneous data of vertical, net horizontal and total (resultant) ground reaction forces were averaged over the support phase of each step over the first and last minutes of constant velocity runs. Foot contact was identified when the vertical ground reaction force exceeded 30 N with the subsequent toe off occurring when it fell below 30 N. Contact time (s), aerial time (s), step frequency (Hz) and step length (m) were also computed.

A linear spring–mass model was used to characterize mechanical lower limb behavior.⁸ Vertical stiffness (kN m^{-1}) was calculated as the ratio of peak vertical forces ($F_{z\text{max}}$ in N) to the maximal vertical downward displacement of center of mass (Δz in m), which was determined by double integration of vertical acceleration of center of mass over time during ground contact. Leg stiffness (kN m^{-1}) was calculated as the ratio of peak vertical forces to the maximum leg spring compression (ΔL in m) [$\Delta z + L_0 - \sqrt{L_0^2 - (0.5 \times \text{running$

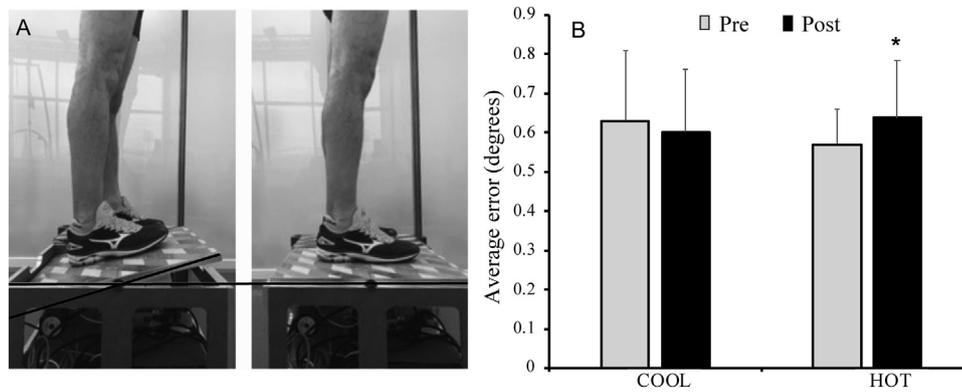


Fig. 1. Proprioceptive acuity during the AMEDA test. (A) Left picture is the deepest dorsiflexion position and right picture is the starting position; (B) the average error was higher post 30 min treadmill run in HOT as compared to COOL. Values are mean \pm SD. * Main effect of condition ($p < 0.05$).

velocity \times contact time)²], both occurring at mid-stance. Initial leg length (L_0 , great trochanter to ground distance in a standing position) was determined from the participant's stature as $L_0 = 0.53 \times$ stature.⁸

Two-dimensional (2D) kinematics were obtained during the self-paced runs using a high-frequency (100 Hz) camera (Basler scA640-120gc, Basler AG, Germany). The camera was mounted on a tripod placed at 1.5 m from the center of the treadmill and was oriented perpendicular to the sagittal plane of the runners to minimize any parallax error. A set of body reflective markers was placed on the left side of the participant's body (Fig. 2). The videos were analyzed frame-by-frame by the same experimenter using a movement analysis software (Tracker, 5.0.5) to determine the marker coordinates used to calculate the angular kinematics.

The segmental angles of the PELVIS, THIGH, SHANK and FOOT were determined relatively to the horizontal line at the time of foot strike (Fig. 2). The joint angles of the HIP, KNEE and ANKLE were then determined. Vertical displacements of the anterior superior iliac spine (ASIS) were determined via video analysis as the difference between the maximal and minimum height of the ASIS across a full stride cycle. Kinetics and kinematics were analyzed over 10 consecutive strides.

Data were analyzed using SPSS 21.0 (IBM, Chicago, IL). Body mass loss and distance covered were analyzed using a one-way repeated-measures ANOVA (2 conditions: HOT vs. COOL). Other parameters were analyzed using a two-way repeated-measures ANOVA [Condition (HOT vs. COOL) \times Time (Onset/first min vs. Endpoint/last min)]. Where significant interaction effects were established, pairwise differences were identified using *Bonferroni* adjustments. $p < 0.05$ were considered statistically significant. Effect size was measured using partial eta-squared (η_p^2) values with $\eta_p^2 \geq 0.06$ representing a moderate effect and $\eta_p^2 \geq 0.14$ a large effect. All values are expressed as mean \pm SD.

3. Results

Rectal temperature displayed an interaction effect ($p = 0.017$, $\eta_p^2 = 0.418$) between time and condition with similar values at the start of the run ($p = 0.914$) but higher values in HOT than COOL at completion ($p = 0.007$). Skin temperature displayed an interaction effect ($p = 0.004$, $\eta_p^2 = 0.542$) due to a tendency to increase in HOT ($p = 0.065$) and to decrease in COOL ($p = 0.084$). RPE displayed an interaction effect ($p = 0.019$, $\eta_p^2 = 0.406$) with an increase in HOT ($p = 0.001$) but not in COOL ($p = 0.813$). Body mass loss was larger in HOT compared to COOL ($-1.1 \pm 0.5\%$ vs. $-0.7 \pm 0.3\%$, $p = 0.044$). All body temperatures, along RPE, HR and TC were higher in HOT than COOL during both the self-paced run and the AMEDA testing

($p < 0.05$, $\eta_p^2 > 0.309$; Table 1). All parameters increased over time ($p < 0.05$), except for skin temperature ($p = 0.525$).

Velocity displayed an interaction effect between time and condition ($p = 0.002$) as it increased from the first to the second half of the run in COOL ($+6.2 \pm 0.1\%$, $p = 0.013$) but not in HOT ($-2.2 \pm 0.1\%$, $p = 0.360$). The average running velocity was slower during the self-paced treadmill run in HOT compared to COOL ($13.9 \pm 1.6 \text{ km h}^{-1}$ vs. $14.7 \pm 1.5 \text{ km h}^{-1}$, $p < 0.001$), corresponding to a $\sim 5\%$ decrease in the total distance covered ($6910 \pm 773 \text{ m}$ vs. $7276 \pm 703 \text{ m}$, $p < 0.001$).

Average error for active movement discrimination displayed an interaction effect ($p = 0.029$, $\eta_p^2 = 0.395$, Fig. 1) with post hoc analyses revealing an increased error after running in HOT ($+11\%$, $p = 0.028$) but not in COOL (-2% , $p = 0.547$).

No interaction effect was found for any of the stride mechanical parameters (all $p > 0.250$, $\eta_p^2 < 0.120$). Step frequency decreased (-2% , $p = 0.038$, $\eta_p^2 = 0.336$) and step length increased ($+3\%$, $p = 0.033$, $\eta_p^2 = 0.352$) from the first to the last minute, but none of them differed between conditions ($p \geq 0.232$, $\eta_p^2 \leq 0.127$, Table 1). Increases in contact time ($+2\%$, $p = 0.224$, $\eta_p^2 = 0.131$) and aerial time ($+4\%$, $p = 0.090$, $\eta_p^2 = 0.239$) between the first and the last minute were not statistically significant (Table 1). Contact ($p = 0.592$, $\eta_p^2 = 0.027$) and aerial ($p = 0.273$, $\eta_p^2 = 0.108$) times were not different between conditions. There was no main effect of condition (all $p > 0.113$, $\eta_p^2 < 0.212$), time (all $p > 0.092$, $\eta_p^2 < 0.237$) or interaction (all $p > 0.159$, $\eta_p^2 < 0.172$) for any of the spring mass characteristics (Table 1). No interaction effect was found for any of the running kinematic parameters (all $p > 0.302$, $\eta_p^2 < 0.096$, Table 1). There was no significant effect of time or condition on segmental and joint angles, except for a time-dependent increase of the PELVIS retroversion angle ($p = 0.025$, $\eta_p^2 = 0.378$) and a decrease of the ANKLE dorsi-flexion angle ($p = 0.045$, $\eta_p^2 = 0.317$).

4. Discussion

This study is the first to evaluate changes in ankle proprioception and running gait pattern induced by a self-paced treadmill run with or without heat stress. The greater thermal, perceptual and cardiovascular strains in hot conditions resulted in a $\sim 5\%$ slower pace as well as an increase in the average error of movement discrimination. Adjustments in spatio-temporal and angular parameters from the onset to the end of the run were similar between the two environments, while spring-mass parameters remained unchanged. Our hypothesis is partly validated since heat stress impairs proprioception, yet without exacerbating run-induced readjustments in stride mechanical pattern. As a whole, this suggests that temperature-related alteration in ankle proprio-

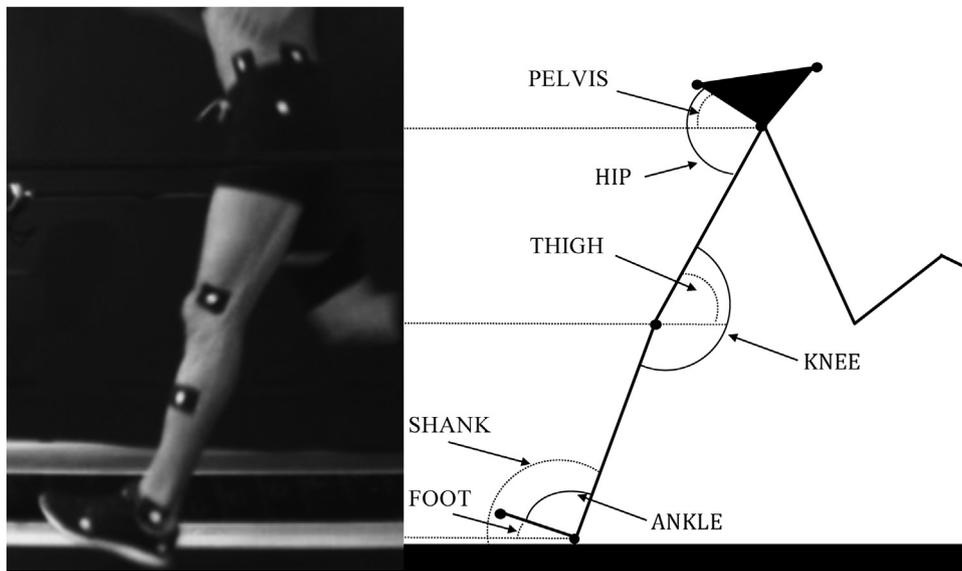


Fig. 2. Schematic drawing of joint angles (plain lines) and segmental angles relative to the horizontal line (dashed line) measured at foot strike.

Table 1
Physiological, perceptual responses and running mechanics data. Data were measured before (Pre) and after (Post) the treadmill run while performing the active movement extend discrimination apparatus testing (AMEDA) (average of 7 min) and during the first (Onset) and last (Endpoint) minute of the 30 min treadmill run (Running).

AMEDA	COOL			HOT	
	Pre	Post		Pre	Post
Trectal (°C)	37.3 ± 0.4	39.3 ± 0.4*	<	37.4 ± 0.3	39.9 ± 0.3 [§]
Tskin (°C)	32.2 ± 1.1	33.1 ± 1.1	<	34.3 ± 0.5	36.1 ± 1.0*
Tbody (°C)	35.5 ± 0.5	36.4 ± 0.4*	<	37.2 ± 0.3	39.0 ± 0.3*
Heart rate (beats min ⁻¹)	62.0 ± 9.3	136.2 ± 13.7*	<	64.2 ± 13.1	150.1 ± 17.7 [§]
Thermal comfort	2.6 ± 0.9	4.0 ± 0.9*	<	3.9 ± 1.2	5.6 ± 0.8*
Running	Onset	Endpoint		Onset	Endpoint
Trectal (°C)	38.0 ± 0.3	39.4 ± 0.4*	<	38.0 ± 0.3	39.7 ± 0.4 [§]
Tskin (°C)	32.2 ± 0.8	31.8 ± 1.1	<	35.7 ± 0.4	36.3 ± 1.1
Tbody (°C)	35.4 ± 0.5	36.4 ± 0.4*	<	37.1 ± 0.3	38.3 ± 0.2*
Heart rate (beats min ⁻¹)	133.4 ± 10.7	173.9 ± 5.9*	<	139.0 ± 10.3	177.9 ± 8.4*
Thermal comfort	3.0 ± 0.7	4.3 ± 1.3*	<	4.5 ± 1.1	6.5 ± 0.5*
RPE	10.0 ± 1.3	14.0 ± 1.8*	<	10.2 ± 1.5	15.9 ± 2.5 [§]
Stride kinematics					
Step length (m)	1.26 ± 0.10	1.30 ± 0.12*		1.28 ± 0.11	1.31 ± 0.14*
Step frequency (Hz)	2.93 ± 0.08	2.85 ± 0.16*		2.90 ± 0.12	2.84 ± 0.17*
Contact time (s)	0.220 ± 0.019	0.226 ± 0.019		0.223 ± 0.020	0.225 ± 0.020
Aerial time (s)	0.121 ± 0.025	0.126 ± 0.030		0.123 ± 0.026	0.128 ± 0.033
Vertical displacement (cm)	11.16 ± 3.51	10.78 ± 1.27		9.91 ± 2.38	10.44 ± 2.80
Spring-mass characteristics					
Peak vertical forces (N)	1886 ± 234	1863 ± 256		1912 ± 257	1866 ± 300
Maximal downward vertical displacement (m)	0.054 ± 0.009	0.051 ± 0.010		0.053 ± 0.007	0.049 ± 0.009
Leg compression (m)	0.116 ± 0.014	0.117 ± 0.017		0.115 ± 0.014	0.114 ± 0.015
Vertical stiffness (kN m ⁻¹)	42.4 ± 12.8	39.3 ± 7.1		36.9 ± 4.5	39.6 ± 5.0
Leg stiffness (kN m ⁻¹)	16.4 ± 2.1	16.2 ± 2.4		16.8 ± 2.2	16.6 ± 2.6
Angular kinematics (°)					
PELVIS	45.2 ± 13.0	47.8 ± 15.3*		49.5 ± 12.4	51.7 ± 14.4*
THIGH	67.2 ± 3.3	66.6 ± 3.0		67.3 ± 4.3	67.4 ± 4.4
SHANK	100.0 ± 3.9	99.1 ± 3.6		99.2 ± 3.8	98.9 ± 4.0
FOOT	10.7 ± 8.8	10.9 ± 7.7		11.1 ± 8.5	12.1 ± 7.2
HIP	112.4 ± 13.1	114.4 ± 15.7		116.8 ± 14.6	118.5 ± 16.5
KNEE	147.2 ± 5.6	147.5 ± 4.3		148.1 ± 5.6	148.5 ± 6.3
ANKLE	89.2 ± 8.8	88.2 ± 9.0*		88.1 ± 8.1	86.8 ± 7.6*

Values are mean ± SD < and > main effect of condition.

[§] HOT different from COOL (Post only).

* Pre/Onset different from Post/Endpoint (all $p < 0.05$).

ception has no or limited influence on treadmill running gait at a constant velocity.

The current data showed that running in HOT increased the average error of movement discrimination at the ankle, while no such changes occurred in COOL. The magnitude of impairment reported in the current study after running in HOT (+0.07 degrees)

is similar to the increase in the dorsiflexion discrimination error (+0.08 degrees) observed previously following passive hyperthermia Tcore reaching 39°C.³ Of note, albeit Tcore was also ≥39°C in COOL, Tcore, Tskin and average body temperature along heart rate were all significantly higher in HOT despite a lower distance covered. The impairment in proprioception following exercising in

HOT, but not COOL, can therefore be attributed to a larger hyperthermic response. This is in line with the recent observation that passive hyperthermia ($T_{\text{core}} \sim 39.0^\circ\text{C}$) impairs the afferent output from the muscle (i.e., depressed H-reflex amplitude) as well as proprioception and postural stability.³ Thus, the impairment of ankle proprioception observed in the current study might be partly attributed to the alterations in the afferent output from muscle receptors due to the combination of hyperthermia³ and fatigue.¹⁵

In contrast to our hypothesis, the heat-induced alterations in ankle proprioception had no influence on run-induced changes in stride mechanical pattern, when assessed at constant velocity (Table 1). The current data are in line with Girard et al.¹⁰ reporting that stride kinematics and leg and vertical stiffness were unchanged at constant-velocity runs.¹⁰ Similarly, a hot water immersion (42°C) up to the level of the maximum gluteal girth for 40 min associated with a significant elevation in core temperature ($38.8 \pm 0.3^\circ\text{C}$) did not affect kinematics during a three 10 min treadmill runs at 70% of MAV in cool conditions.¹⁶ However, rectal temperature did not exceed 39°C in those two previous studies. The current study adds that self-paced treadmill running in the heat inducing hyperthermia and impairing proprioception did not accentuate joint and segmental angles at foot strike, step frequency and length.

Independently of environmental conditions, the current results showed a significant increase in step length and decrease in step frequency accompanied by non-significant increases in aerial and contact times from the beginning to the end of the run. These data are in line with the observation that running velocity can be maintained during fatiguing high-intensity treadmill runs through longer step and slower step frequency.¹⁷ Contrastingly, increases in step frequency and contact time, and a decrease in aerial time and step length developed during a constant run at 95% of MAV.¹⁸ Giving that mechanical adjustments remain 'task dependent'¹⁷ the differences between the latter findings and the current study may be linked to a slower running velocity (70% vs. 95% MAV), a longer protocol (30 min vs. ~ 9 min) and/or the use of a different model (treadmill vs. overground) in the current study.

The current results obtained on an instrumented treadmill displayed unchanged values for peak vertical forces, maximal downward vertical displacement, leg compression, and vertical and leg stiffness. Similarly, unchanged leg and vertical stiffness were observed after an exhaustive 2000 m run on an indoor track at constant velocity (13 km h^{-1}).¹⁹ Conversely, leg and vertical stiffness can decrease significantly during a constant velocity treadmill run to exhaustion (57 ± 19 min) at approximately 80% of peak oxygen uptake.²⁰ Thus, 30 min may be not long enough to modify the elastic properties of the leg muscles for trained runners in the current study.

Moreover, the present study showed that angular kinematics changed over the course of the fatiguing run with the longer strides being accompanied by an upswing of the PELVIS and a decrease in ANKLE dorsiflexion angle. Those changes are in line with previous studies showing specific changes in ankle and trunk angles at foot strike with fatigue,^{21,22} such as a 3.2% decrease in ankle dorsiflexion at foot strike when running with dorsiflexors fatigue.²³ Contrastingly, the increase in trunk flexion (4°) and decrease in trunk extension (3°) with fatigue reported by Koblbauer et al.²² differ from the PELVIS retroversion observed in the current study. Thus, with the development of fatigue, moderate stride kinematic adjustments occurred in association with few segmental compensations in lower limbs between the beginning and the end of the treadmill running, yet both occurred irrespective of environmental conditions.

Importantly, the current interpretations should be limited to the condition of the protocol (i.e., treadmill running) as runners may take advantage of the moving belt compared to overground

running.²⁴ Thus, fine adjustments to ankle dorsiflexion angle may be more important during overground running and the proprioceptive cost of heat stress may become evident when overground running in a way that it is not seen in treadmill running. Specific adjustments may also be seen in response to the change in velocity between conditions during an overground self-paced run. Future studies are required whilst running overground at different velocities or for different duration in outdoor hot ambient conditions.

5. Conclusion

In summary, higher thermal, cardiovascular and perceptual strain under heat stress decreased running velocity and impaired proprioception. However, the fatigue-induced changes in spatio-temporal parameters and joint angles were not dependent of heat stress when controlling the velocity. Thus, although heat stress impaired proprioception and resulted in the adoption of a slower pacing strategy, heat stress had no or limited influence on running gait at a given velocity.

Acknowledgments

The authors thank Clint Hansen for his methodological input. The authors thank Mohammed Aziz Farooq for his support with the statistical analysis. The authors thank the participants for their involvement. The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. This study was internally funded by Aspetar Orthopedic and Sports Medicine Hospital. This project was conducted using an instrumented treadmill that was funded by QNRF (NPRP 4-760-3-217).

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