Am J Physiol Regul Integr Comp Physiol 312: R101–R107, 2017.
First published November 30, 2016; doi:10.1152/ajpregu.00431.2016.

RESEARCH ARTICLE | *Exploiting Environmental Factors to Improve Health and Performance*

Passive heat acclimation improves skeletal muscle contractility in humans

S. Racinais, M. G. Wilson, and J. D. Périard

Aspetar Orthopaedic and Sports Medicine Hospital, Athlete Health and Performance Research Centre, Doha, Qatar

Submitted 5 October 2016; accepted in final form 23 November 2016

Racinais S, Wilson MG, Périard JD. Passive heat acclimation improves skeletal muscle contractility in humans. *Am J Physiol Regul Integr Comp Physiol* 312: R101–R107, 2017. First published November 30, 2016; doi:10.1152/ajpregu.00431.2016.—The aim of this study was to investigate the effect of repeated passive heat exposure (i.e., acclimation) on muscle contractility in humans. Fourteen non-heat-acclimated males completed two trials including electrically evoked twitches and voluntary contractions in thermoneutral conditions [Cool: 24°C, 40% relative humidity (RH)] and hot ambient conditions in the hyperthermic state (Hot: 44–50°C, 50% RH) on consecutive days in a counterbalanced order. Rectal temperature was ~36.5°C in Cool and was maintained at ~39°C throughout Hot. Both trials were repeated after 11 days of passive heat acclimation (1 h per day, 48–50°C, 50% RH). Heat acclimation decreased core temperature in Cool (−0.2°C, $P < 0.05$), increased the time required to reach 39°C in Hot (+9 min, $P < 0.05$) and increased sweat rate in Hot (+0.7 liter/h, $P < 0.05$). Moreover, passive heat acclimation improved skeletal muscle contractility as evidenced by an increase in evoked peak twitch amplitude both in Cool (20.5 ± 3.6 vs. 22.0 ± 4.0 N·m) and Hot (20.5 ± 4.7 vs. 22.0 ± 4.0 N·m) (+9%, $P < 0.05$). Maximal voluntary torque production was also increased both in Cool (145 ± 42 vs. 161 ± 36 N·m) and Hot (125 ± 36 vs. 145 ± 30 N·m) (+17%, $P < 0.05$), despite voluntary activation remaining unchanged. Furthermore, the slope of the relative torque/electromyographic linear relationship was improved postacclimation ($P < 0.05$). These adjustments demonstrate that passive heat acclimation improves skeletal muscle contractile function during electrically evoked and voluntary muscle contractions of different intensities both in Cool and Hot. These results suggest that repeated heat exposure may have important implications to passively maintain or even improve muscle function in a variety of performance and clinical settings.

heat therapy; temperature; hyperthermia; exercise; performance

AN ACUTE RISE in muscle temperature within the physiological range (i.e., 34–42°C) increases muscle contractility (5), force (7), and power (2, 3) in a dose-response manner at a rate of 2–5% per 1°C increase (42). Consequently, because of the effect of the environment on muscle temperature, muscle force and power are commonly lower in a cold environment (16, 31) and increased in a warm environment (1, 11). Notwithstanding, there is a ceiling above which increasing environmental temperature does not improve muscle force and power production (39), and environmental conditions inducing an increase in core body temperature lead to an acute decrease in volitional muscle force output (27, 40, 48). However, the chronic adaptations to repeated heat exposures in human skeletal muscle remain unknown.

When exposed to heat for a few days, humans show relatively important and rapid autonomic adaptations enhancing thermoregulation and increasing work capacity in hot environments (34). Classically described adaptations include a decrease in resting core temperature (23), along with reduced core and skin temperatures (9) and an increased sweat rate (8) during heat exposure. Heat acclimation also causes an expansion of plasma volume (12, 32). Collectively, these adaptations improve heat transfer to the environment, effectively "sparing" blood for the rest of the circulation (9) and relieving circulatory strain (24). Yet, despite a relatively clear understanding of the cardiovascular adaptations related to heat acclimation (36), the impact of heat acclimation upon skeletal muscle function remains unclear.

To our knowledge, the only study conducted in humans reported that 10 wk of 8 h/day localized passive heating increased muscle cross-sectional area and maximal voluntary contraction (MVC) strength (14). In rats, a single exposure to 41°C heat for 1 h increased cell proliferation and muscle protein content (49). In vitro studies also suggest that 1 h (50) to 4 days (15) of heat stress facilitates hypertrophy in cultured cells. Collectively, these studies suggest that repeated heat exposure (i.e., heat acclimation) might improve muscle contractile function. Understanding the effect of repeated heat exposure on human muscle function might have numerous sport and clinical applications. For example, it was recently reported that repeated passive heat exposure may induce mitochondrial adaptations (47), promote muscle capillary growth (22), and improve cardiovascular health (4), potentially benefiting patients with limited exercise capabilities. By following the same model, repeated passive heat exposure could be a valuable tool to improve skeletal muscle function in humans.

Therefore, the aim of this study was to investigate the effect of passive heat acclimation (11 days, 1 h per day) on muscle contractility in humans. Based on available in vitro and animal studies, it was hypothesized that heat acclimation would improve human skeletal muscle force and contractility in both hot and temperate conditions.

MATERIALS AND METHODS

Ethical Approval

The project was approved by the scientific committee of the hospital (CMO/000033/fj) and by an external (Anti-Doping Labora-

Address for reprint requests and other correspondence: S. Racinais, Athlete Health and Performance Research Centre, Aspetar Orthopaedic and Sports Medicine Hospital, PO Box 29222, Doha, Qatar (e-mail: sebastien.racinais@aspetar.com).

tory Qatar) ethics committee (F2013000004). The procedures complied with the Declaration of Helsinki regarding human experimentation. Written informed consent was obtained from all participants before the beginning of testing.

Participants

Fourteen male participants (age: 33 ± 8 yr, body mass: 74 ± 7 kg and height: 177 ± 7 cm) volunteered for the study. The study was conducted at the end of the winter (average temperature range 14–27°C) to avoid seasonal heat acclimatization. Participants were healthy and recreationally active in endurance or team sports but not involved in resistance training. They maintained their usual level of activity during the study. Participants completed a Medical History Questionnaire and Physical Activity Readiness Questionnaire (PAR-Q) before being admitted to the study. None of the subjects suffered from neural or muscular pathologies at the time of the experiment. None reported a history of heat-related illness.

Experimental Design

General procedures. After a familiarization session was completed, participants completed testing trials in temperate conditions [24°C and 40% relative humidity (RH)] in a normothermic state (Cool) and in hot conditions (44–50°C and 50% RH) in a hyperthermic state (Hot), at the same time of day on consecutive days in a counter-balanced order. After these testing trials, participants were passively heat acclimated for 11 days, 1 h per day. Participants then repeated the two initial testing trials (i.e., Cool and Hot) in the same order and at the same time of day postacclimation. All trials were performed in an environmental chamber (Tescor, Warminster, PA).

Familiarization session. Participants were seated with ankle and knee angles of 90° and 100°, respectively, and the right foot was securely strapped to a dynamometric pedal (Captels, St. Mathieu de Treviers, France). The tibial nerve was electrically stimulated (voltage 400 V, rectangular pulse of 0.2 ms) via a high-voltage stimulator (Digitimer DS7AH, Digitimer, Hertfordshire, UK) through a cathode placed in the popliteal cavity and an anode placed distally to the patella. The intensity was adjusted for each participant by progressively increasing amperage (10-mA increment) until a plateau in twitch mechanical response (i.e., peak twitch, PT). Participants were then familiarized with performing MVCs of the plantar flexors until they were able to produce 3 MVCs with less than 3% variation. Finally, participants were trained to produce voluntary contractions at specific intensities (i.e., 10, 25, 50, and 75% of MVC) by following a line representing torque production on a computer screen placed in front of them. The same equipment, positions, and procedures were used for all testing trials. The dynamometric pedal was calibrated before each test session in the conditions of the experiment.

Temperate normothermic trial (Cool). After instrumentation (i.e., rectal probe and skin temperature sensors, see below), participants rested for 30 min in an upright seated position in the environmental chamber. Thereafter, the minimum electrical intensity required to elicit PT was determined and multiplied by 1.5 to define the stimulation intensity used during the subsequent test. Participants then underwent six electrical stimulations of the tibial nerve at rest followed by six electrical stimulations during a submaximal contraction performed at a constant intensity (determined during the familiarization session to correspond at 10% of MVC) to ensure a constant level of background muscle activity (40). Thereafter, participants performed a 5-s MVC followed by submaximal contractions at 50, 25, and 75% of the previous MVC to estimate the torque/electromyographic (EMG) relationship (38). A superimposed and potentiated twitch were evoked during the plateau of the MVC and 4 s after the MVC, respectively, using doublet stimulation at 100 Hz. The MVC and submaximal contractions were always performed in the same order and the complete set was repeated three times.

Hot hyperthermic trial (Hot). During the resting period, the environmental temperature and relative humidity were initially set at 50°C and 50% RH, respectively. Once participants reached a rectal temperature of 39°C, the environmental temperature was adjusted between 44°C and 50°C to ensure that rectal temperature was clamped at ~39°C for the testing procedure. The testing procedure was the same as Cool and lasted for ~1 h in all conditions.

Heat acclimation. Participants remained in the environmental chamber for 1 h. Environmental conditions were set at 50°C and 50% RH for the first 10 min and adjusted to 48°C and 50% RH for the remaining 50 min. Participants were seated on a chair, talking, or playing cards for the first 20–30 min, and resting quietly thereafter. They were allowed to drink at libitum (temperate water) and body mass changes remained within 2% in 95% of the sessions. All participants completed all sessions of passive heat acclimation except one participant who exited the room 4 to 10 min before the end on *days 1*, *3*, and *5* becausse of discomfort. The participant completed the 60-min exposure on the other 8 sessions and was included in the study.

Measurement

Physiological monitoring. Core temperature was monitored using a rectal probe inserted 15 cm beyond the anal sphincter (Ellab, Hilleroed, Denmark). Mean skin temperature was calculated as 0.3 × chest temperature + 0.3 × arm temperature + 0.2 × thigh temperature + 0.2 × lower leg temperature (44). Local skin temperatures and heart rate were measured telemetrically (Equivital, Cambridge, UK). Sweat rate was calculated from changes in nude body mass and the amount water consumed over the trial duration.

Electrically evoked twitch. The mechanical response to the electrically evoked stimulations were recorded from the dynamometric pedal using MP35 hardware (Biopac Systems, Santa Barbara, CA) and dedicated software (BSL Pro Version 3.6.7, Biopac Systems). The signal was amplified (gain = 200) and recorded at a sampling frequency of 10 kHz. The six twitches evoked at rest and during the contraction at 10% MVC were respectively averaged and analyzed for amplitude (PT), contraction time (CT), and half-relaxation time (HRT). In addition, the rate of torque development (RTD) was calculated as PT/CT (10).

Isometric contractions. Muscle torque was recorded as described above for evoked twitches. In addition, EMG activity of the soleus was recorded using bipolar surface Ag/AgCl electrodes (Ambu Blue sensor T, Ambu) with a recording diameter of 9 mm and an interelectrode distance of 3 cm. The EMG signal was recorded using MP35 hardware and software (see *Electrically evoked twitch* for details), amplified (gain = 1,000), filtered (30–500 Hz), and recorded at a sampling frequency of 10 kHz. Before electrode placement, the skin was shaved and scrubbed to remove surface layers of dead skin, hair, and oil, and a reference electrode was placed over the patella. The EMG activity was computed as the root mean square (RMS) of the signal.

Voluntary activation. The ratio of the amplitude of the superimposed twitch over the amplitude of the potentiated twitch (both doublets) was used to assess the level of voluntary activation (VA) during MVC as follow: VA (%) = (1-superimposed twitch/potentiated twitch) × 100.

Torque/EMG relationship. The slope of the relative torque/EMG relationship was calculated for each participant from the torque and EMG activity at 25, 50, 75, and 100% of MVC normalized as a percentage of the values recorded during the preacclimation Cool trial for each participant.

Statistical Analyses

Data were coded in SPSS 21.0 (SPSS, Chicago, IL). The effects of hyperthermia (Cool vs. Hot) and time (preacclimation vs. postacclimation) were analyzed for each variable by two-way analysis of

variance (ANOVA) for repeated measures (2 conditions × 2 times). ANOVA assumptions were verified preceding all statistical analyzes; Greenhouse-Geisser corrections were applied where appropriate. In case of significant interaction (condition × time), LSD (Least Squared Difference) was used to compare the effect of condition at each time interval and the effect of time in each condition. Effect-sizes are described in terms of partial η-squared (η^2, with $\eta^2 \geq 0.06$ representing a moderate effect and $\eta^2 \geq 0.14$ a large effect). Data are reported as mean (SD) and the level of statistical significance was set at $P < 0.05$.

RESULTS

Thermoregulatory Responses

Environmental testing conditions (Table 1) were hotter ($P < 0.001$, $\eta^2 = 0.998$) and more humid ($P < 0.001$, $\eta^2 = 0.967$) in Hot than Cool but were similar pre- and postacclimation (temperature: $P = 0.836$, $\eta^2 = 0.003$; RH: $P = 0.903$, $\eta^2 = 0.001$; Table 1). The time required to reach the target testing core temperature of 39°C in Hot was longer post- than preacclimation (68 ± 13 vs. 59 ± 15 min, $P = 0.005$, $\eta^2 = 0.469$). Mean skin temperature during the tests was higher in Hot than Cool ($P < 0.001$, $\eta^2 = 0.994$) without a significant effect of acclimation ($P = 0.215$, $\eta^2 = 0.116$) (Table 1). Mean rectal temperature during the tests was higher in Hot than Cool ($P < 0.001$, $\eta^2 = 0.976$). Although an interaction effect was not observed ($P = 0.604$, $\eta^2 = 0.021$), mean rectal temperature during the tests significantly decreased from pre- to postacclimation in Cool ($P = 0.026$) but not Hot ($P = 0.152$) as core temperature was maintained ~39°C (Table 1). Sweat rate was higher in Hot than Cool ($P < 0.001$, $\eta^2 = 0.883$) and increased with acclimation ($P = 0.001$, $\eta^2 = 0.583$). There was also an interaction effect ($P < 0.001$, $\eta^2 = 0.707$) due to an increased sweat rate in Hot ($P < 0.001$) but not Cool ($P = 0.730$). Mean heart rate during the tests was higher in Hot than Cool ($P < 0.001$, $\eta^2 = 0.920$), also demonstrating an interaction effect ($P = 0.031$, $\eta^2 = 0.310$) due to a decrease from pre- to postacclimation in Hot ($P = 0.013$) but not Cool ($P = 0.419$).

Electrically Evoked Twitch

Resting PT amplitude (Fig. 1, Table 2) was similar in Hot and Cool ($P = 0.978$, $\eta^2 < 0.001$) and significantly increased from pre- to postacclimation ($P = 0.049$, $\eta^2 = 0.266$), without an interaction effect ($P = 0.978$, $\eta^2 < 0.001$). The PT amplitude measured with a constant and controlled background muscle contraction at 10% MVC (Table 2) was higher in Hot than Cool ($P = 0.019$, $\eta^2 = 0.356$) and significantly increased

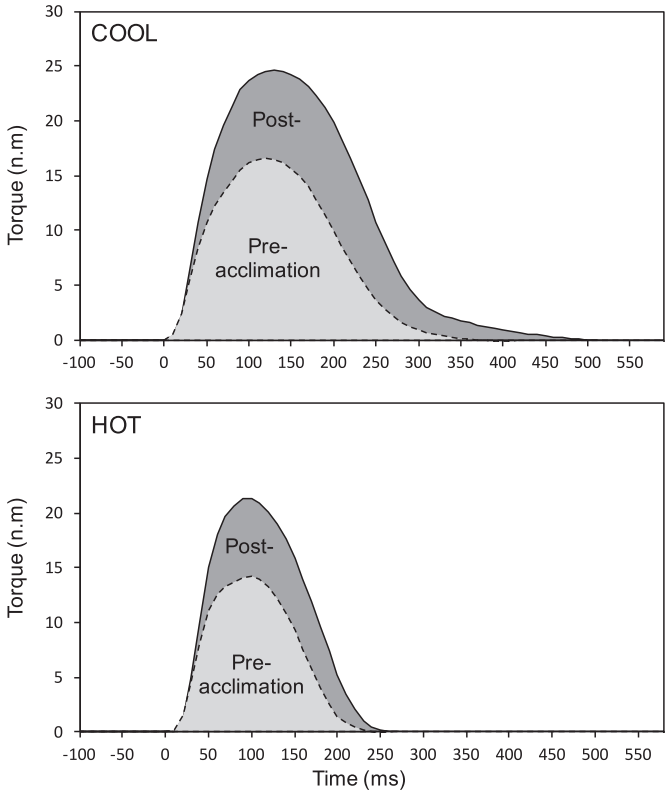

Fig. 1. Muscle twitch. Electrically evoked muscle twitches on a relaxed muscle in one representative participant. Acute exposure to heat (Hot, *bottom*) reduced contraction time and half-relaxation time without affecting amplitude relative to temperate (Cool, *top*) conditions. Chronic passive heat exposure (i.e., heat acclimation) increased peak twitch amplitude.

Table 1. *Mean environmental conditions, thermoregulatory and heart rate responses during the tests in temperate (Cool) and hot (Hot) conditions before and after passive heat acclimation*

	Preacclimation		Postacclimation	
	Cool	Hot	Cool	Hot
Environmental conditions				
Temperature, °C	24.1 (0.2)	45.8 (1.3)*	24.0 (0.2)	46.0 (0.8)*
Relative humidity, %	37.1 (2.7)	49.4 (4.1)*	37.5 (3.3)	49.2 (3.7)*
Thermoregulatory responses				
Core temperature, °C	36.6 (0.4)	39.2 (0.3)*	36.4 (0.4)†	39.1 (0.3)*
Skin temperature, °C	30.8 (0.5)	38.9 (0.7)*	30.7 (0.5)	38.6 (0.7)*
Sweat rate, liter/h	0.1 (0.3)	1.3 (0.4)*	0.1 (0.1)	2.0 (0.7)*†
Heart rate, beats/min	74 (8)	126 (9)*	78 (13)	116 (9)*†

Values are means (SD). *Significant differences between Hot and Cool ($P < 0.05$). †Significant differences between Post and Pre (post hoc analyses, $P < 0.05$).

Table 2. *Mechanical responses to an electrically evoked muscle twitch at rest and with a constant and controlled background muscle contraction at 10% MVC in temperate (Cool) and hot (Hot) conditions before and after passive heat acclimation*

	Preacclimation		Postacclimation	
	Cool	Hot	Cool	Hot
Relaxed muscle				
PT, N·m	20.5 (3.6)	20.5 (4.7)	22.0 (4.0)	22.0 (4.0)
CT, ms	126 (18)	80 (9)*	124 (15)	79 (8)*
HRT, ms	107 (20)	80 (12)*	111 (28)	83 (12)*
RTD, N·m·ms^{-1}	0.16 (0.03)	0.26 (0.06)*	0.18 (0.03)	0.28 (0.05)*
Controlled background activity (10%)				
PT, N·m	19.2 (3.7)	21.0 (4.5)	20.5 (3.8)	22.6 (4.2)*
CT, ms	112 (15)	76 (8)*	113 (14)	76 (7)*
HRT, ms	78 (14)	56 (6)*	83 (11)	60 (8)*
RTD, N·m·ms^{-1}	0.17 (0.03)	0.28 (0.06)*	0.18 (0.04)	0.30 (0.06)*

Values are means (SD). PT, peak twitch amplitude; CT, contraction time; HRT, half-relaxation time; RTD, rate of torque development. *Significant differences between Hot and Cool ($P < 0.05$). †Significant main effect of acclimation (i.e., increase from pre- to postacclimation, $P < 0.05$).

from pre- to postacclimation ($P = 0.032$, $\eta^2 = 0.308$), without an interaction effect ($P = 0.823$, $\eta^2 < 0.004$).

Both CT and HRT measured at rest and with a constant and controlled background muscle contraction at 10% MVC were shorter in Hot than Cool ($P < 0.001$, $\eta^2 \geq 0.644$), without an interaction effect ($P \geq 0.491$, $\eta^2 \leq 0.037$). There were no changes in CT and HRT from pre- to postacclimation ($P \geq 0.257$, $\eta^2 \leq 0.098$), except for an increase in HRT with a 10% MVC background contraction ($P = 0.005$, $\eta^2 = 0.460$). The RTD was faster in Hot than Cool ($P < 0.001$, $\eta^2 \geq 0.864$) without demonstrating an interaction effect ($P \geq 0.466$, $\eta^2 \leq 0.042$) but show a tendency to increase from pre- to postacclimation ($0.058 \leq P \leq 0.067$, $0.004 \leq \eta^2 \leq 0.249$).

Maximal Torque

MVC torque production was significantly lower in Hot than Cool ($P < 0.001$, $\eta^2 = 0.700$), along with a significantly lower EMG activity of the soleus ($P < 0.001$, $\eta^2 = 0.764$) and VA ($P = 0.008$, $\eta^2 = 0.432$) (Table 3). Passive heat acclimation significantly increased MVC torque from pre- to postacclimation ($P = 0.004$, $\eta^2 = 0.484$) without modifying EMG activity of the soleus ($P = 0.495$, $\eta^2 = 0.037$) and VA ($P < 0.491$, $\eta^2 = 0.037$). There were no interaction effects between acclimation and environmental testing conditions on torque production, EMG activity, and VA ($P \geq 0.588$, $\eta^2 \leq 0.023$).

Relative Torque/EMG Relationship

The slope of the relative torque/EMG relationship (Fig. 2) was 1.0 ± 0.1 in Cool preacclimation, 1.2 ± 0.4 in Cool postacclimation, 1.3 ± 0.4 in Hot preacclimation, and 1.8 ± 0.9 in Hot postacclimation. The relative slope was significantly higher in Hot than Cool ($P < 0.001$, $\eta^2 = 0.624$) and increased from pre- to postacclimation ($P = 0.052$, $\eta^2 = 0.261$) without an interaction effect ($P = 0.165$, $\eta^2 = 0.143$).

DISCUSSION

The aim of this study was to determine the effect of passive heat acclimation upon muscle contractile function in humans. Along with classically reported adaptations to heat acclimation (e.g., decreased core temperature at rest and increased sweat rate in the heat), our data demonstrate that passive heat acclimation improves skeletal muscle contractile function during both normothermic and in the hyperthermic humans. These improvements were verified in measures obtained at rest and during contractions at different intensities (10, 25, 50, 75% MVC), as well as in different neuromuscular parameters: an increase in electrically evoked peak twitch amplitude (Fig. 1),

Table 3. *Maximal voluntary contraction responses in temperate (Cool) and hot (Hot) conditions before and after passive heat acclimation*

	Preacclimation		Postacclimation	
	Cool	Hot	Cool	Hot
Torque, N·m	145 (42)	125 (36)*	161 (36)	145 (30)*
RMS Soleus, mV	0.28 (0.06)	0.18 (0.06)*	0.31 (0.09)	0.20 (0.08)*
VA, %	92.7 (9.0)	81.1 (19.7)*	93.9 (5.7)	82.2 (17.3)*

VA, voluntary activation. Values in mean (SD). *Significantly lower in Hot than Cool ($P < 0.05$). †Significant global increase from pre- to postacclimation ($P < 0.05$).

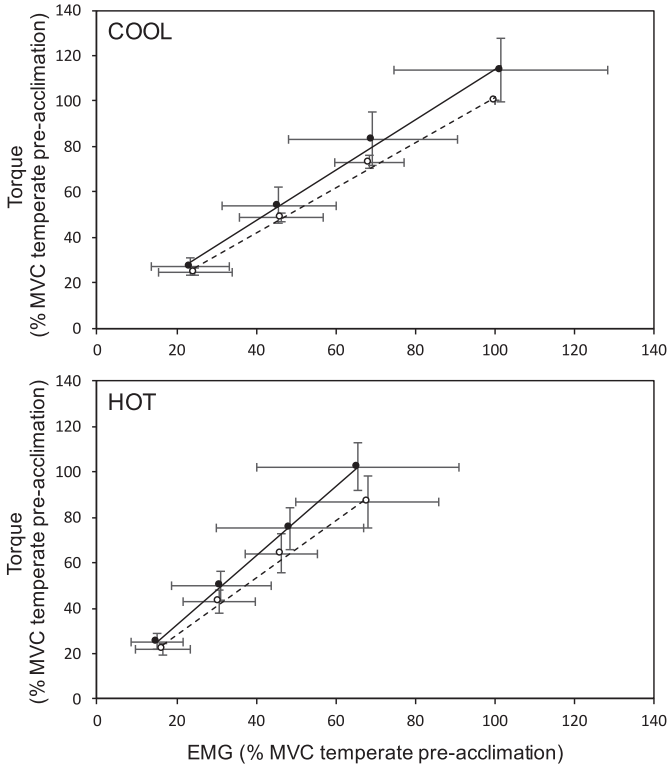

Fig. 2. Relative torque/electromyographic (EMG) relationship in temperate (Cool, *top*) and hot (Hot, *bottom*) ambient conditions. Passive heat acclimation (solid line) increased the relative torque/EMG relationship in both Cool and Hot conditions compared with preacclimation (dashed line).

an increase in maximal torque production at a similar level of voluntary activation (Table 3), and an improvement of the relative torque/EMG linear relationship (Fig. 2). This infers that passive heat acclimation improves skeletal muscle contractile function in humans, irrespective of thermal state.

Influence of Acute and Repeated Heat Exposure on Contractile Properties

The PT amplitude was not different in Cool and Hot. However, CT and HRT were lower in Hot than Cool, and RTD was faster in Hot than Cool. This result confirms classic in vitro animal (45) and in vivo human (7) studies reporting decreases in CT and HRT when muscle temperature increases. The PT amplitude represents the number of interactions between actin and myosin, whereas CT and HRT are linked to the rate of Ca^{2+} release and reuptake (10). These results therefore suggest that an acute increase in temperature increased the rate of cross-bridges formation and opening, rather than the total number of cross-bridges being formed in response to a given action potential.

As displayed in Fig. 1, repeated heat exposure significantly increased PT from pre- to postacclimation. However, this increase occurred without significant changes in CT and HRT, expect for one of the HRT values increasing (potentially driven by the higher PT amplitude). The different pattern of changes in PT compared with CT and HRT (Table 2) confirm that the acute changes in CT and HRT in Hot do not affect PT amplitude in humans (7, 35). Moreover, this study extends these observations by demonstrating that the decrease in CT

and HRT induced by acute heat exposure was not modified after 11 days of passive heat acclimation in humans. The increase in PT without changes in CT suggests an increase in RTD from pre- to postacclimation; however the increase in RTD did not reach significance in the current study (Table 2). Taken together, these results suggest that the increase in PT observed during both Cool and Hot after heat acclimation is mainly explained by a change in the number cross-bridge formation or the force per cross-bridge, with potential alterations in the kinetics of formation of the cross-bridges remaining to be confirmed.

Some in vitro studies have previously reported an acute increase in maximum tetanic force with increasing muscle temperature, although this relationship might not exist in all muscle groups or when temperature continues to rise toward physiologically relevant temperatures (5, 45, 46). Indeed, the increase in maximum tetanic force in vitro is likely related to improvements in contractile protein binding when temperature increases from relatively low temperatures (46), but this improvement does not seem to persist when temperature fluctuates in the standard range experienced in vivo (37). In the current study, we did not observe any acute differences in PT between Hot and Cool, suggesting that acute heat exposure has only a minimal effect on muscle contractility in human. Whereas a limitation in the current study is the absence of muscle temperature measurements, previous studies from our group using similar whole body passive heating procedures suggest that muscle temperatures were likely ~35°C (Cool) and ~38°C–39°C (Hot) (35, 41). Taken together, the absence of acute effect of heat exposure on PT, the increase in PT from pre- to postacclimation at the same core temperatures, and the fact that this increase was present in both Hot and Cool conditions, suggest that the pre- to postacclimation improvement in muscle contractility was not due to an acute effect of temperature.

Passive Heat Acclimation Improves Muscle Function and Torque

Our results show that despite a lack of influence of acute heat exposure on PT, both MVC and VA were significantly lower in hyperthermic state than normothermic state (Table 3). This confirms previous reports that hyperthermia can decrease force or torque production during an MVC in relation to alterations in the central and peripheral nervous systems (33, 40). Moreover, the current data suggest that these alterations (i.e., lower MVC and VA in Hot) persist postacclimation.

Notwithstanding, an increase in MVC torque was observed in both normothermic and hyperthermic state following passive heat acclimation relative to preacclimation, which was not accompanied by changes in EMG activity. This suggests an improvement in peripheral muscle function. It has to be acknowledged that EMG activity should be interpreted with caution when comparing different environmental conditions as skin temperature might directly or indirectly affect EMG amplitude (43). However, in the current study, EMG was compared from pre- to postacclimation in similar environments and at similar skin temperatures (Table 1). The absence of variation in EMG activity from pre- to postacclimation was further confirmed by the absence of variation in VA. It therefore seems that the increase in MVC torque production flowing passive heat acclimation is related to adaptations in peripheral muscle function, with contractile property improvements observed during both Cool and Hot.

The improvements in electrically evoked PT amplitude and MVC torque production for a given VA and neural drive (i.e., EMG) were accompanied by an upward shift in the relative torque/EMG relationship (Fig. 2) following passive heat acclimation. Since the seminal work of Moritani and deVries (26) on EMG, a shift in the torque/EMG relationship has been used to differentiate the peripheral and neural responses to various interventions. Using this classic approach, we demonstrated passive heat exposure induced peripheral adaptations of a similar type than those previously reported after several weeks of resistance training (6, 17, 26). However, future studies are warranted to determine the magnitude of these passive adaptations compared with training, as well as the effect of combining resistance training and heat exposure.

Potential Pathways for Improved Skeletal Muscle Contractility

A previous study reported that localized heat stress increased mammalian target rapamycin (mTOR) signaling molecule proliferation after a single bout of resistance training, suggesting that heat stress might enhance protein synthesis in skeletal muscle (18). Ten weeks of localized heat stress for 8 h/day has also been reported to increase muscle cross-sectional area and MVC force production (14). The present study adds to these reports in humans, demonstrating that 1 h/day of passive heat acclimation for 11-days increases muscle torque through an improvement in muscle contractile function. The molecular pathways associated with the increases in muscle contractility noted in the current study remain to be elucidated. However, in vitro studies have suggested that stress proteins such as heat shock protein 72 (HSP72) may facilitate hypertrophy in cultured cells (15, 50). In vivo animal studies have shown that a single session of passive heat stress increases muscle HSP72 expression and increases cell proliferation, protein content, and muscle mass (19, 30, 49). The pathways for this muscle hypertrophy may include a calcineurin-dependent signaling pathway (19), activation of the Akt/mTOR signaling pathway (51), and a decrease in nuclear factor-κB signaling (30). Interestingly, it appears that these pathways are related to HSP upregulation, as a deficiency in heat shock transcription factor 1 (HSF1, a protein playing a crucial role in inducing HSP) suppresses the heat stress-associated increase in muscle mass in mice (29). However, because of the multitude of potential pathways involved, the increase in muscle protein content after a single heat exposure (in rats) does not appear directly related to HSP72 expression (21). Future studies should therefore investigate the effect of heat acclimation on muscle cross-sectional area and its relationship with changes in muscle contractile function, as well as intramuscular HSPs in humans.

Perspectives and Significance

It was recently debated whether heat acclimation does (25) or does not (28) improve endurance exercise performance in temperate conditions. The present study adds to the debate extending beyond the typical hematological and cardiovascular adaptations, with passive heat acclimation improving muscle contractile properties during both hyperthermic and normother-

mic states. Importantly, this benefit was obtained via passive rather active heat acclimation, which is clinically relevant for populations unable to exercise. Passive heat therapy has recently been suggested to improve vascular function (4). At the muscle level, repeated passive heating can promote mitochondrial adaptations in mice skeletal muscle (47) and capillary growth in human skeletal muscle (22). Such adaptations have been suggested as potential treatments for populations with a limited capacity to exercise such as the elderly, injured athletes, or patients (4, 47). Our data add to this range of adaptations in that repeated passive heat exposure could also improve skeletal muscle contractile function. In the animal model (i.e., rats), it has been reported that heat stress increases protein content and facilitates the recovery of atrophied muscle after an immobilization period (13), or following a chemically induced muscle injury (21). Moreover, heat acclimation together with exercise training has also been shown to increase muscle strength more than exercise training alone in rat soleus muscles (20). Thus, based on the same model recently suggesting that repeated passive heat exposure could improve cardiovascular health in patients with limited exercise capabilities (4), repeated passive heat exposure may represent a novel rehabilitative method to increase or maintain human muscle function.

However, it has to be acknowledged that these adaptations were obtained with a relatively large external heat load in the current study. The minimum stimulus required to trigger muscle adaptations remains to be determined along with the relative contribution of the repeated increase in core and muscle temperatures. The current results should also be confirmed with different populations and protocols before being considered for use in clinical settings. Finally, although each of the parameters measured in the current study showed only limited statistical or clinical significance, all parameters showed concordant changes allowing for a 17% increase in MVC.

In conclusion, passive heat acclimation improved skeletal muscle function in humans during both normothermia and hyperthermia. This improvement was manifested as an increase in peak twitch amplitude, an increase in MVC torque production, as well as an improvement in the relative torque/EMG linear relationship. These improvements were consistent across measures obtained at rest and at different contraction intensities (10, 25, 50, 75% and MVC). The present study highlights a novel passive method to improve muscle function via heat acclimation that may be used with athletes and patients during a period of musculoskeletal unloading, such as postsurgical immobilization.

ACKNOWLEDGMENTS

The authors thank Mohammed Aziz Farooq for support with the statistical analyzes. The authors thank the participants for their commitment.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

S.R. conceived and designed research; S.R., M.G.W., and J.D.P. performed experiments; S.R. analyzed data; S.R., M.G.W., and J.D.P. interpreted results of experiments; S.R. prepared figures; S.R. drafted manuscript; S.R., M.G.W., and J.D.P. edited and revised manuscript; S.R., M.G.W., and J.D.P. approved final version of manuscript.

REFERENCES

1. **Ball D, Burrows C, Sargeant AJ.** Human power output during repeated sprint cycle exercise: the influence of thermal stress. *Eur J Appl Physiol Occup Physiol* 79: 360–366, 1999. doi:10.1007/s004210050521.
2. **Bergh U, Ekblom B.** Influence of muscle temperature on maximal muscle strength and power output in human skeletal muscles. *Acta Physiol Scand* 107: 33–37, 1979. doi:10.1111/j.1748-1716.1979.tb06439.x.
3. **Binkhorst RA, Hoofd L, Vissers AC.** Temperature and force-velocity relationship of human muscles. *J Appl Physiol* 42: 471–475, 1977.
4. **Brunt VE, Howard MJ, Francisco MA, Ely BR, Minson CT.** Passive heat therapy improves endothelial function, arterial stiffness and blood pressure in sedentary humans. *J Physiol* 594: 5329–5342, 2016. doi:10.1113/JP272453.
5. **Close R, Hoh JF.** Influence of temperature on isometric contractions of rat skeletal muscles. *Nature* 217: 1179–1180, 1968. doi:10.1038/2171179a0.
6. **Colson S, Pousson M, Martin A, Van Hoecke J.** Isokinetic elbow flexion and coactivation following eccentric training. *J Electromyogr Kinesiol* 9: 13–20, 1999. doi:10.1016/S1050-6411(98)00025-X.
7. **Davies CT, Young K.** Effect of temperature on the contractile properties and muscle power of triceps surae in humans. *J Appl Physiol* 55: 191–195, 1983.
8. **Dill DB, Hall FG, Edwards HT.** Changes in composition of sweat during acclimatization to heat. *Am J Physiol* 123: 412–419, 1938.
9. **Eichna LW, Park CR, Nelson N, Horvath SM, Palmes ED.** Thermal regulation during acclimatization in a hot, dry (desert type) environment. *Am J Physiol* 163: 585–597, 1950.
10. **Fitts RH, Holloszy JO.** Effects of fatigue and recovery on contractile properties of frog muscle. *J Appl Physiol* 45: 899–902, 1978.
11. **Girard O, Bishop DJ, Racinais S.** Hot conditions improve power output during repeated cycling sprints without modifying neuromuscular fatigue characteristics. *Eur J Appl Physiol* 113: 359–369, 2013. doi:10.1007/s00421-012-2444-3.
12. **Glaser EM.** Acclimatization to heat and cold. *J Physiol* 110: 330–337, 1949. doi:10.1113/jphysiol.1949.sp004442.
13. **Goto K, Honda M, Kobayashi T, Uehara K, Kojima A, Akema T, Sugiura T, Yamada S, Ohira Y, Yoshioka T.** Heat stress facilitates the recovery of atrophied soleus muscle in rat. *Jpn J Physiol* 54: 285–293, 2004. doi:10.2170/jjphysiol.54.285.
14. **Goto K, Oda H, Kondo H, Igaki M, Suzuki A, Tsuchiya S, Murase T, Hase T, Fujiya H, Matsumoto I, Naito H, Sugiura T, Ohira Y, Yoshioka T.** Responses of muscle mass, strength and gene transcripts to long-term heat stress in healthy human subjects. *Eur J Appl Physiol* 111: 17–27, 2011. doi:10.1007/s00421-010-1617-1.
15. **Goto K, Okuyama R, Sugiyama H, Honda M, Kobayashi T, Uehara K, Akema T, Sugiura T, Yamada S, Ohira Y, Yoshioka T.** Effects of heat stress and mechanical stretch on protein expression in cultured skeletal muscle cells. *Pflugers Arch* 447: 247–253, 2003. doi:10.1007/s00424-003-1177-x.
16. **Hackney AC, Shaw JM, Hodgdon JA, Coyne JT, Kelleher DL.** Cold exposure during military operations: effects on anaerobic performance. *J Appl Physiol (1985)* 71: 125–130, 1991.
17. **Häkkinen K, Komi PV.** Electromyographic changes during strength training and detraining. *Med Sci Sports Exerc* 15: 455–460, 1983. doi:10.1249/00005768-198315060-00003.
18. **Kakigi R, Naito H, Ogura Y, Kobayashi H, Saga N, Ichinoseki-Sekine N, Yoshihara T, Katamoto S.** Heat stress enhances mTOR signaling after resistance exercise in human skeletal muscle. *J Physiol Sci* 61: 131–140, 2011. doi:10.1007/s12576-010-0130-y.
19. **Kobayashi T, Goto K, Kojima A, Akema T, Uehara K, Aoki H, Sugiura T, Ohira Y, Yoshioka T.** Possible role of calcineurin in heating-related increase of rat muscle mass. *Biochem Biophys Res Commun* 331: 1301–1309, 2005. doi:10.1016/j.bbrc.2005.04.096.
20. **Kodesh E, Horowitz M.** Soleus adaptation to combined exercise and heat acclimation: physiogenomic aspects. *Med Sci Sports Exerc* 42: 943–952, 2010. doi:10.1249/MSS.0b013e3181c3ac3f.
21. **Kojima A, Goto K, Morioka S, Naito T, Akema T, Fujiya H, Sugiura T, Ohira Y, Beppu M, Aoki H, Yoshioka T.** Heat stress facilitates the regeneration of injured skeletal muscle in rats. *J Orthop Sci* 12: 74–82, 2007. doi:10.1007/s00776-006-1083-0.
22. **Kuhlenhoelter AM, Kim K, Neff D, Nie Y, Blaize AN, Wong BJ, Kuang S, Stout J, Song Q, Gavin TP, Roseguini BT.** Heat therapy promotes the expression of angiogenic regulators in human skeletal

muscle. *Am J Physiol Regul Integr Comp Physiol* 311: R377–R391, 2016. doi:10.1152/ajpregu.00134.2016.
23. **Ladell WS.** Assessment of group acclimatization to heat and humidity. *J Physiol* 115: 296–312, 1951. doi:10.1113/jphysiol.1951.sp004672.
24. **MacDonald DKC, Wyndham CH.** Heat transfer in man. *J Appl Physiol* 3: 342–364, 1950.
25. **Minson CT, Cotter JD.** CrossTalk proposal: Heat acclimatization does improve performance in a cool condition. *J Physiol* 594: 241–243, 2016. doi:10.1113/JP270879.
26. **Moritani T, deVries HA.** Neural factors versus hypertrophy in the time course of muscle strength gain. *Am J Phys Med* 58: 115–130, 1979.
27. **Morrison S, Sleivert GG, Cheung SS.** Passive hyperthermia reduces voluntary activation and isometric force production. *Eur J Appl Physiol* 91: 729–736, 2004. doi:10.1007/s00421-004-1063-z.
28. **Nybo L, Lundby C.** CrossTalk opposing view: Heat acclimatization does not improve exercise performance in a cool condition. *J Physiol* 594: 245–247, 2016. doi:10.1113/JP270880.
29. **Ohno Y, Egawa T, Yokoyama S, Nakai A, Sugiura T, Ohira Y, Yoshioka T, Goto K.** Deficiency of heat shock transcription factor 1 suppresses heat stress-associated increase in slow soleus muscle mass of mice. *Acta Physiol (Oxf)* 215: 191–203, 2015. doi:10.1111/apha.12600.
30. **Ohno Y, Yamada S, Sugiura T, Ohira Y, Yoshioka T, Goto K.** Possible role of NF-κB signals in heat stress-associated increase in protein content of cultured C2C12 cells. *Cells Tissues Organs* 194: 363–370, 2011. doi:10.1159/000323324.
31. **Oksa J, Rintamäki H, Mäkinen T, Martikkala V, Rusko H.** EMG-activity and muscular performance of lower leg during stretch-shortening cycle after cooling. *Acta Physiol Scand* 157: 71–78, 1996. doi:10.1046/j.1365-201X.1996.452172000.x.
32. **Patterson MJ, Stocks JM, Taylor NA.** Sustained and generalized extracellular fluid expansion following heat acclimation. *J Physiol* 559: 327–334, 2004. doi:10.1113/jphysiol.2004.063289.
33. **Périard JD, Christian RJ, Knez WL, Racinais S.** Voluntary muscle and motor cortical activation during progressive exercise and passively induced hyperthermia. *Exp Physiol* 99: 136–148, 2014. doi:10.1113/expphysiol.2013.074583.
34. **Périard JD, Racinais S, Sawka MN.** Adaptations and mechanisms of human heat acclimation: Applications for competitive athletes and sports. *Scand J Med Sci Sports* 25, *Suppl* 1: 20–38, 2015. doi:10.1111/sms.12408.
35. **Périard JD, Racinais S, Thompson MW.** Adjustments in the force-frequency relationship during passive and exercise-induced hyperthermia. *Muscle Nerve* 50: 822–829, 2014. doi:10.1002/mus.24228.
36. **Périard JD, Travers GJS, Racinais S, Sawka MN.** Cardiovascular adaptations supporting human exercise-heat acclimation. *Auton Neurosci* 196: 52–62, 2016. doi:10.1016/j.autneu.2016.02.002.
37. **Place N, Yamada T, Zhang S-J, Westerblad H, Bruton JD.** High temperature does not alter fatigability in intact mouse skeletal muscle fibres. *J Physiol* 587: 4717–4724, 2009. doi:10.1113/jphysiol.2009.176883.
38. **Racinais S, Blonc S, Jonville S, Hue O.** Time of day influences the environmental effects on muscle force and contractility. *Med Sci Sports Exerc* 37: 256–261, 2005. doi:10.1249/01.MSS.0000149885.82163.9F.
39. **Racinais S, Chamari K, Hachana Y, Bartagi Z, Blonc S, Hue O.** Effect of an acute hot and dry exposure in moderately warm and humid environment on muscle performance at different times of day. *Int J Sports Med* 27: 49–54, 2006. doi:10.1055/s-2005-837503.
40. **Racinais S, Gaoua N, Grantham J.** Hyperthermia impairs short-term memory and peripheral motor drive transmission. *J Physiol* 586: 4751–4762, 2008. doi:10.1113/jphysiol.2008.157420.
41. **Racinais S, Girard O.** Neuromuscular failure is unlikely to explain the early exercise cessation in hot ambient conditions. *Psychophysiology* 49: 853–865, 2012. doi:10.1111/j.1469-8986.2012.01360.x.
42. **Racinais S, Oksa J.** Temperature and neuromuscular function. *Scand J Med Sci Sports* 20, *Suppl* 3: 1–18, 2010. doi:10.1111/j.1600-0838.2010.01204.x.
43. **Racinais S.** Hot ambient conditions shift the Force/EMG relationship. *Springerplus* 2: 317, 2013. doi:10.1186/2193-1801-2-317.
44. **Ramanathan NL.** A new weighting system for mean surface temperature of the human body. *J Appl Physiol* 19: 531–533, 1964.
45. **Segal SS, Faulkner JA, White TP.** Skeletal muscle fatigue in vitro is temperature dependent. *J Appl Physiol (1985)* 61: 660–665, 1986.
46. **Stephenson DG, Williams DA.** Calcium-activated force responses in fast- and slow-twitch skinned muscle fibres of the rat at different temperatures. *J Physiol* 317: 281–302, 1981. doi:10.1113/jphysiol.1981.sp013825.
47. **Tamura Y, Matsunaga Y, Masuda H, Takahashi Y, Takahashi Y, Terada S, Hoshino D, Hatta H.** Postexercise whole body heat stress additively enhances endurance training-induced mitochondrial adaptations in mouse skeletal muscle. *Am J Physiol Regul Integr Comp Physiol* 307: R931–R943, 2014. doi:10.1152/ajpregu.00525.2013.
48. **Thomas MM, Cheung SS, Elder GC, Sleivert GG.** Voluntary muscle activation is impaired by core temperature rather than local muscle temperature. *J Appl Physiol (1985)* 100: 1361–1369, 2006. doi:10.1152/japplphysiol.00945.2005.
49. **Uehara K, Goto K, Kobayashi T, Kojima A, Akema T, Sugiura T, Yamada S, Ohira Y, Yoshioka T, Aoki H.** Heat-stress enhances proliferative potential in rat soleus muscle. *Jpn J Physiol* 54: 263–271, 2004. doi:10.2170/jjphysiol.54.263.
50. **Yamashita-Goto K, Ohira Y, Okuyama R, Sugiyama H, Honda M, Sugiura T, Yamada S, Akema T, Yoshioka T.** Heat stress facilitates stretch-induced hypertrophy of cultured muscle cells. *J Gravit Physiol* 9: 145–146, 2002.
51. **Yoshihara T, Naito H, Kakigi R, Ichinoseki-Sekine N, Ogura Y, Sugiura T, Katamoto S.** Heat stress activates the Akt/mTOR signalling pathway in rat skeletal muscle. *Acta Physiol (Oxf)* 207: 416–426, 2013. doi:10.1111/apha.12040.