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ORIGINAL ARTICLE

Six weeks of localized heat therapy does not affect muscle mass, strength and contractile properties in healthy active humans

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Abstract

Purpose Animal and human studies have shown that repeated heating may induce skeletal muscle adaptations, increasing muscle strength. The aim of this study is to investigate the effect of 6 weeks of localized heating on skeletal muscle strength, volume and contractile properties in healthy humans.

Methods Fifteen active participants (8 males/7 females, 35 ± 6 years, 70 ± 14 kg, 173 ± 7 cm, average training of 87 min per week) were subjected to 6 weeks of single-leg heat therapy. Heat pads were applied for 8 h/day, 5 days/week, on one randomly selected calf of each participant, while the contralateral leg acted as control. The heat pads increased muscle temperature by 4.6 ± 1.2 °C ($p < 0.001$). Every 2 weeks, participants were tested for morphological (MRI), architectural (ultrasound), contractile (electrically evoked twitch), and force (isometric and isokinetic) adaptations.

Results Repeated localized heating did not affect the cross-sectional area ($p = 0.873$) or pennation angle ($p = 0.345$) of the gastrocnemius muscles; did not change the evoked peak twitch amplitude ($p = 0.574$) or rate of torque development ($p = 0.770$) of the plantar flexors; and did not change maximal voluntary isometric ($p = 0.214$) or isokinetic ($p = 0.973$) plantar flexor torque.

Conclusion Whereas previous studies have observed improved skeletal muscle function following whole-body and localized heating in active and immobilized humans, respectively, the current data suggested that localized heating may not be a potent stimulus for muscle adaptations in active humans.

Keywords Heat stress · Human skeletal muscle · Hypertrophy · Force · Isokinetic

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Abbreviations

ANOVA	Analysis of variance
CON	Control leg
CSA	Cross sectional area
FOV	Field of view
HOT	Heated leg
iMVC	Isometric maximal voluntary contraction
RTD	Rate of torque development
VA	Voluntary activation
W0	Pre-test
W2	Test after 2 weeks
W4	Test after 4 weeks
W6	Test after 6 weeks

Introduction

Heat is often used as a traditional therapy in many cultures to treat a variety of health conditions. For example, repeated passive heat exposures have been shown to improve quality

of life (Sobajima et al. 2015; Beever 2010), improve cardiovascular health (Brunt et al. 2016; Sobajima et al. 2013), and is associated with a lower risk of fatal cardiovascular disease and all-cause mortality (Laukkanen et al. 2015). In vitro (Goto et al. 2003) and animal (Uehara et al. 2004) studies have also suggested that repeated heat exposures may increase protein content at the level of the skeletal muscle. Rodent studies have further shown that repeated heat exposure may reduce muscle atrophy during immobilization (Selsby and Dodd 2005) and facilitate the recovery of atrophied muscle after immobilization (Goto et al. 2004; Selsby et al. 2007).

In humans, repeated passive heat exposures have been reported to induce skeletal muscle adaptations increasing peak torque of the plantar flexors (Racinais et al. 2017) and knee extensors (Goto et al. 2011; Kim et al. 2020). Moreover, it has also been shown that repeated passive heat exposure could enhance mitochondrial function and increase mitochondrial biogenesis (Hafen et al. 2018; Hawley et al. 2018). Whilst whole-body heat exposures improved muscle function after 11 days (Racinais et al. 2017), the benefits of localized heat exposures have been observed following substantially longer interventions lasting 8–10 weeks (Goto et al. 2011; Kim et al. 2020). An exception would be Hafen et al. (2019) reporting improved muscle function following 10 days of localized heat exposures, albeit in immobilized participants experiencing muscle atrophy. As such, the time-course of adaptations is relatively unknown in humans undertaking localized heat exposure. Such information is fundamental to understand the therapeutic potential of this modality, and consequently its application in sport and clinical situations (e.g., injury, illness, and immobilization).

Moreover, resistance training induces strength gains specific to the training position (Jones et al. 1989; Kitai and Sale 1989), the contraction velocity (Seger et al. 1998) and the contraction regimen (Tomberlin et al. 1991; Bishop et al. 1991). However, this questions the specificity of the adaptations conferred by 'passive' heat training and the resultant effect on the torque-velocity and torque-joint angle relationships. The nature of these adaptions is important to characterize to allow clinician to integrate heat therapy within their rehabilitation toolbox.

Therefore, the aim of this study was to investigate the kinetics of adaptations in muscle strength, contractile properties and volume during 6 weeks of localized heating in healthy humans. Based on previous studies, it was hypothesized that localized heat therapy would increase muscle function, while the effect on velocity and angle of maximal torque, along the kinetics of adaptations were exploratory.

Methods

Participants

From an initial group of 17 participants, 2 participants withdrew due to personal reasons. 15 participants completed the entire study (8 males, 7 females, 35 ± 6 year, 70 ± 14 kg, 173 ± 7 cm). The study was conducted at the end of winter to avoid seasonal heat acclimatization. Participants were healthy and physically active in endurance or team sports (working as a physiotherapist or fitness coach during the day plus training an average of 87 min per week, independent of the week, $p = 0.374$), but not resistance training. All participants were informed about the possible risks and signed an informed consent prior to the commencement of the study. The experimental procedures were conducted in accordance with the world medical association declaration of Helsinki (Ethical Principles for Medical Research Involving Human Subjects) and approved by an external IRB.

Experimental design

One week after a familiarization session, participants underwent pre-experimental testing (W0) followed by 6 weeks of localized heat exposures, with additional tests at 2, 4 and 6 weeks (W2, W4 and W6). Each test session included neuromuscular testing (electrically evoked and voluntary contractions) as well as muscle imaging. The tests were performed in a thermoneutral environment (~ 20 °C), 21 h (imaging) to 40 h (neuromuscular test) after the last localized heating. Localized heating was administered by applying heat pads on one lower leg (targeting the *gastrocnemius*), with the contralateral leg acting as control. The control (CON) and heated (HOT) legs were counterbalanced based on the strength measures from the familiarization session.

Thermal intervention

Two adhesive heat pads (The Heat Company, Altenmarkt, Austria) were placed on the *gastrocnemius* from 8:00 am to 4:00 pm, for 5 days per week, for 6 consecutive weeks. The heat pads were applied directly on the skin, and further secured with an elasticated tubular bandage. Heat pads measured 9 × 13 cm each, and were positioned abreast covering the medial and lateral *gastrocnemius* muscles. The duration of heating was based on a previous study reporting increases in quadriceps cross-sectional area (CSA) and strength after applying heat pads for 8 h/day during 10 weeks (Goto et al. 2011).

Participants were active during the day (e.g., professional fitness coach) but performed their personal exercise routine after removing the pads. Compliance was verified using a self-completed training log.

Muscle temperature

The temperature of the gastrocnemius muscle (at a depth of ~ 2 cm) was continuously monitored during 6 h of localized heating in six participants using a flexible thermistor (MAC flexible probe, Ellab). The thermistor was autoclaved according to the manufacturer recommendations (steam 121 °C) and inserted via a catheter (16 Gauge) after local anesthesia (2 mL of Xylocaine). Due to thermistor movement in one participant, only five participants were analyzed.

Neuromuscular testing

All neuromuscular tests were performed on an isokinetic dynamometer (Biodex System 3, Shirely, NY, USA). The participants lay supine, with hip and knee fully extended, and their arms crossed in front of their chest. One foot was positioned on the foot adapter connected to the head of the dynamometer and secured with two straps. The rotation axis of the lever arm was aligned with the rotation axis of the ankle. Torque and position were recorded at 1000 Hz using MP35 hardware (Biopac Systems, Santa Barbra, CA) and a specific software (BSL Pro Version 3.6.7, Biopac Systems). The signal was amplified (gain = 500) and calibrated before each test. Once the first leg was tested, participants were allowed to rest for ~ 5 min before testing the contralateral leg (counterbalanced order between participants, constant order within participants). The same equipment and procedures were used during all the testing sessions. Data were analyzed using a custom LabVIEW script (LabVIEW, National Instrument, TX, USA).

Electrically evoked twitch. The tibial nerve was stimulated by a high-voltage stimulator (Digitimer DS7AH, Digitimer, Hertfordshire, UK) through a cathode placed in the popliteal cavity and an anode placed distal to the patella (voltage 400 V, rectangular pulse of 0.2 ms). The intensity was adjusted by gradually increasing amperage (10 mA increment) until a plateau in twitch amplitude was observed. The minimum electrical intensity needed to evoke a plateau was multiplied by 1.5 to determine the stimulation intensity used during the test (Racinais et al. 2013). Participants then received six electrical stimulations of the tibial nerve at rest. The six twitches evoked at rest were averaged and analyzed for amplitude, contraction time, half relaxation time, maximal rate of force development and maximal rate of force relaxation.

Rate of torque development (RTD). Participants performed five explosive contractions interspersed by 20 s rest periods. The participants were encouraged and instructed to "push as fast and as hard as possible" during each contraction (~ 1 s). The three best trials were averaged and analyzed during the first 50 ms, 100 ms and 200 ms of the contraction.

Isometric torque. Participants performed 3 iMVC lasting 5 s, interspersed by 60 s of rest in between. In addition, a superimposed and potentiated twitch was evoked during the plateau of the iMVC and 4 s after the iMVC, respectively, using doublet stimulations at 100 Hz. The ratio of the amplitudes of the superimposed over the potentiated twitch were used to assess the level of voluntary activation (VA) as: VA (%) = (1 − superimposed twitch/potentiated twitch)*100.

Isokinetic contractions. Maximal isokinetic strength was assessed during slow ($60°s^{-1}$) and fast ($120°s^{-1}$) concentric contractions as well as during an eccentric contraction ($-30°s^{-1}$). Each set included five maximal consecutive contractions, with a resting period of 60 s between sets. Range of motion were standardized from 20-degrees dorsiflexion to 45-degrees plantarflexion. Peak isokinetic torque was defined as the average of three highest attained values and the corresponding angles of maximal torques were extracted.

Imaging

Cross-sectional areas. Patients were positioned supine in a 1.5-T MRI scanner (MR B19, Siemens, Erlangen, Germany), with the feet first, the ankle in neutral position and the foot at about 20 degree of plantar flexion. Two coils were used to extend the coverage of the field-of-view (FOV), also allowing for parallel imaging techniques. Three sets of 30 transverse planes (total 90 slices) were acquired. Scanning ranged from above the knee femoral condyle to the Achilles tendon providing full coverage of the calf muscles. T1 spin echo contiguous axial images were performed with the following parameters repletion time:730, echo time:14, FOV:320, slice thikness:6 SG:0, Matrix: 320X240, NEX:1. The images were evaluated for CSA using a semi-automated custom MATLAB script (R2017a The MathWorks Inc, Natick, MA).

Ultrasound. Muscle thickness, pennation angle, and fascicle length of the medial gastrocnemius were determined from images taken along the longitudinal axis of the muscle belly utilizing a two-dimensional, B-mode ultrasound (12 MHz probe; depth 8 cm; FOV 14 × 47 mm) (Logiq E, GE Healthcare, IL, USA). The measurement site was determined at a point corresponding to 30% of shank length (measured as lateral tibial condyle to lateral malleolus) distal from the medial tibial condyle along the muscle belly (Kumagai et al. 2000). Ultrasound assessments were undertaken with the participants lying prone, with hip and knee in neutral position and after 5 min of inactivity.

Statistical analysis

Analyses were undertaken with SPSS (version 25.0; SPSS, Chicago, IL). The effects of condition (HOT and CON) and time (week 0, week 2, week 4 and week 6) were analyzed with a two-way analysis of variance (ANOVA) for repeated measures (2 conditions × 4 times) for the electrically evoked twitch, RTD and isometric torque; and with an ANOVA (2 conditions × 4 times × 3 velocities) for isokinetic torque. Greenhouse–Geisser corrections were applied in case of non-sphericity of the data (Mauchly's test). Sidak post hoc analysis was performed where significant interaction effects were evident. Statistical significance was set at $p < 0.05$. 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 presented as means ± SD.

Results

None of the interventions statistically depended on sex (all $p \geq 0.088$) and data were, therefore, gathered for further analyses.

Muscle temperature

Muscle temperature increased from 33.5 ± 0.8 °C at rest to 37.3 ± 0.9 °C after 3 h of heating ($p = 0.005$), and 37.6 ± 1.0 °C after 6 h of heating ($p = 0.005$).

Electrically evoked peak twitch

There was no significant effect for condition (all $p \geq 0.731$, $\eta^2 = 0.01$), time ($p \geq 0.320$, $\eta^2 = 0.09$) or interaction (all $p \geq 0.365$ $\eta^2 = 0.00$) for amplitude, contraction time, and half relaxation time (Table 1). There was no significant effect for condition (both $p \geq 0.792$, $\eta^2 = 0.01$), time ($p \geq 0.419$, $\eta^2 = 0.07$) or interaction ($p \geq 0.805$ $\eta^2 = 0.00$) on maximal rate of force development and maximal rate of force relaxation (Table 1).

Rate torque development

There was no effect for condition (all $p \geq 0.122$, $\eta^2 = 0.17$), time ($p \geq 0.090$; $\eta^2 = 0.14$) or interaction ($p \geq 0.245$, $\eta^2 = 0.00$) on any RTD measures (Table 2).

Maximal torque

There was no effect of condition ($p = 0.556$, $\eta^2 = 0.03$) or interaction ($p = 0.214$, $\eta^2 = 0.00$) on iMVC (Fig. 1), but there was a significant effect of time ($p = 0.003$, $\eta^2 = 0.20$) due to an increase from week 1 to 4 (12 ± 3 Nm, $p = 0.005$). No significant effects for condition ($p = 0.231$, $\eta^2 = 0.11$), time ($p = 0.216$, $\eta^2 = 0.11$) or interaction ($p = 0.154$, $\eta^2 = 0.00$) were observed for VA.

Isokinetic torque

There was no effect of condition ($p = 0.951$, $\eta^2 = 0.00$), time ($p = 0.075$; $\eta^2 = 0.17$) or condition by time interaction ($p = 0.973$, $\eta^2 = 0.01$) on isokinetic torque (Fig. 2). There was an effect of velocity ($p < 0.001$, $\eta^2 = 0.91$; all post hoc $p \leq 0.001$), but it did not depend on time ($p = 0.939$, $\eta^2 = 0.02$), condition ($p = 0.380$, $\eta^2 = 0.07$) or condition by time interaction ($p = 0.143$, $\eta^2 = 0.11$).

There was no effect of condition ($p = 0.571$, $\eta^2 = 0.03$), time ($p = 0.370$; $\eta^2 = 0.08$) or condition by time interaction ($p = 0.552$, $\eta^2 = 0.06$) on the angle of maximal isokinetic torque (Fig. 2). There was an effect of velocity

Table 1 Mechanical responses to an electrically evoked muscle twitch in control (CON) and heated leg (HOT) across 6 weeks of passive heat therapy

		W0	W2	W4	W6
PT (Nm)	CON	15.3 ± 3.7	15.9 ± 3.4	15.76 ± 3.9	15.9 ± 3.3
	HOT	15.7 ± 4.5	16.1 ± 4.2	15.2 ± 3.9	15.5 ± 4.3
CT (ms)	CON	144.9 ± 8.1	146.4 ± 11.3	147.8 ± 9.6	150.3 ± 12.9
	HOT	145.1 ± 9.1	149 ± 10.5	146.1 ± 10.6	147.4 ± 9.2
HRT (ms)	CON	91.6 ± 12.1	91.6 ± 11.9	94.7 ± 13.1	91.6 ± 9.8
	HOT	93.4 ± 12.8	91.5 ± 10.2	92.1 ± 11.6	92 ± 11.9
MRFD (Nm ms^{-1})	CON	0.184 ± 0.043	0.190 ± 0.043	0.188 ± 0.047	0.188 ± 0.038
	HOT	0.184 ± 0.053	0.191 ± 0.050	0.185 ± 0.048	0.184 ± 0.051
MRFR (Nm ms^{-1})	CON	− 0.137 ± 0.036	− 0.143 ± 0.036	− 0.137 ± 0.044	− 0.143 ± 0.033
	HOT	− 0.136 ± 0.040	− 0.146 ± 0.040	− 0.137 ± 0.051	− 0.138 ± 0.046

Values are means (SD)

PT peak twitch amplitude, *CT* contraction time, *HRT* half contraction time, *MRFD* maximal rate of force development, *MRFR* maximal rate of force relaxation

W0, W2, W4, W6: test before and after 2, 4 and 6 weeks of intervention, respectively

Table 2 Rate of torque development in control (CON) and heated leg (HOT) across 6 weeks of passive heat therapy

		W0	W2	W4	W6
RTD_{50} (Nm ms^{-1})	CON	6.7 ± 2.7	6.6 ± 3.6	6.7 ± 5.0	6.7 ± 4.7
	HOT	5.5 ± 2.7	7.1 ± 4.7	6.5 ± 3.6	5.9 ± 2.5
RTD_{100} (Nm ms^{-1})	CON	35.6 ± 8	33.9 ± 12.4	30.2 ± 12	32.9 ± 11.7
	HOT	30.4 ± 8.7	29.8 ± 12.6	31.2 ± 12	31.3 ± 9.3
RTD_{200} (Nm ms^{-1})	CON	84.4 ± 24.1	86.9 ± 25.8	80.9 ± 28.1	88.2 ± 3
	HOT	83.7 ± 21.5	86.1 ± 26.1	80.6 ± 25.3	86.4 ± 25.3

Values are means (SD)

RTD Rate of torque development, RTD_{50} first 50 ms of the contraction, RTD_{100} 100 ms of the contraction, RTD_{200} 200 ms of the contraction

W0, W2, W4, W6: test before and after 2, 4 and 6 weeks of intervention, respectively

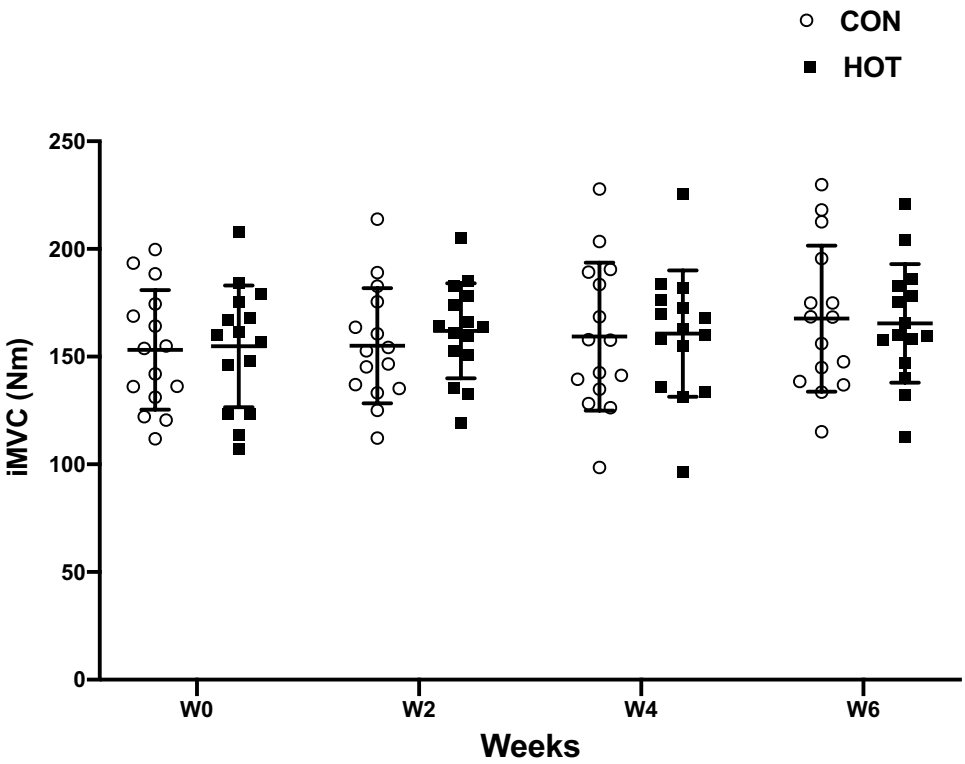

Fig. 1 Individual and mean (SD) maximal torque during an isometric maximal voluntary contraction (iMVC) of the control (CON) and heated leg (HOT) before (W0) and after 2, 4 and 6 weeks of localized heat exposures (W2, W4, W6)

($p < 0.001$, $\eta^2 = 0.96$; all post hoc $p \leq 0.001$), that depended on time ($p = 0.002$, $\eta^2 = 0.25$) and condition ($p = 0.018$, $\eta^2 = 0.28$) but not condition by time interaction ($p = 0.237$, $\eta^2 = 0.10$), nor any post hoc effect of time or condition at any velocity (all $p \geq 0.079$).

Cross-sectional area

Representative MRI images before and after 6-week of localized heating are presented in Fig. 3. There was no significant effect for condition ($p = 0.701$; $\eta^2 = 0.02$), time ($p = 0.111$; $\eta^2 = 0.20$) or interaction ($p = 0.873$; $\eta^2 = 0.00$) on CSA.

Ultrasound

There was no effect of condition ($p = 0.971$; $\eta^2 = 0.00$) or interaction ($p = 0.317$; $\eta^2 = 0.00$) on fascicle length (Table 3), but there was an effect of time ($p = 0.027$, $\eta^2 = 0.32$) with increases from W0 to W2 ($p = 0.004$), W2–W4 ($p = 0.004$) and W2–W6 ($p = 0.014$). There was no effect of condition ($p = 0.404$; $\eta^2 = 0.06$), time ($p = 0.941$; $\eta^2 = 0.01$) or interaction ($p = 0.345$; $\eta^2 = 0.00$) on pennation angle. There was no effect of condition ($p = 0.433$; $\eta^2 = 0.05$) time ($p = 0.067$; $\eta^2 = 0.18$) or interaction ($p = 0.530$; $\eta^2 = 0.06$) on muscle thickness (Table 3).

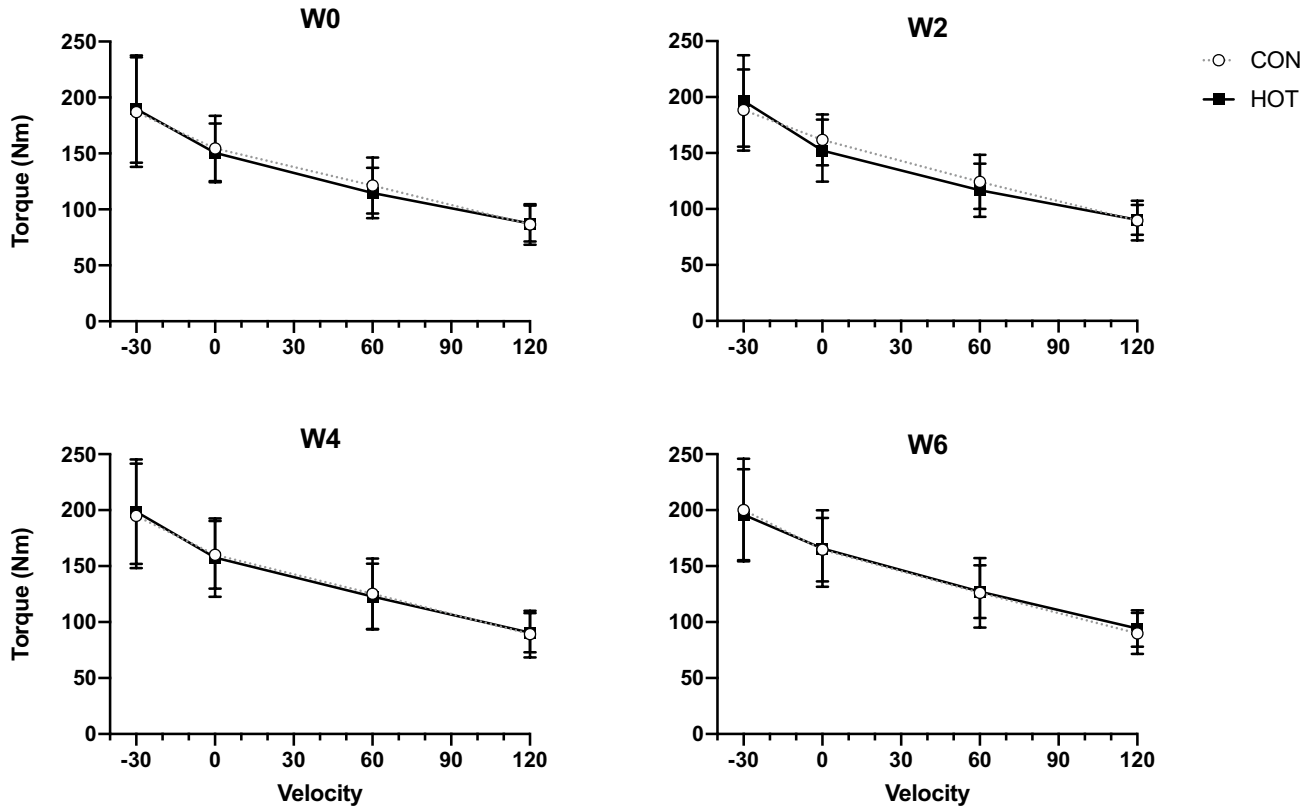

Fig. 2 Mean (SD) isometric (velocity = 0) and isokinetic (velocity = − 30, 60, 120°s^{-1}) torque of the control (CON) and heated leg (HOT). Values before (W0) and after 2, 4 and 6 weeks of localized heat exposures (W2, W4, W6)

Discussion

The aim of this study was to investigate the time course of muscle hypertrophy and increase in muscle force in response to repeated local muscle heating. Contrary to the original hypothesis, the current data showed no benefits following 6 weeks of daily muscle heating on hypertrophy or strength gains compared to a non-heated contralateral limb in healthy active humans. Importantly, this observation was consistent across a range of measures including rate of torque development, maximal isometric torque, and concentric (slow and fast) and eccentric isokinetic torques. This was further supported by no changes in muscle contractile properties evaluated by electrically evoked twitch, as well as by the absence of muscle hypertrophy or other structural adaptations assessed by MRI and ultrasound imaging.

Effect of training and activity

The current observations differ from previous studies reporting improvements in muscle strength following 8–10 weeks of localized heat exposures (Goto et al. 2011; Kim et al. 2020). It is, however, in accordance with another recent study (Stadnyk et al. 2018) showing that adding local repeated heat stress during 12 weeks of resistance training had no effect on hypertrophy and strength gains. This questions the additive effect of a thermal stress to a mechanical stress. Indeed, part of the literature demonstrating that localized heat exposures may improve muscle function originates from immobilized participants experiencing muscle atrophy, and hence not benefitting from any mechanical stimulus (Hafen et al. 2019). Moreover, the potential benefit of heat therapy during disuse is also supported by findings in rodent studies showing an attenuated decrease in muscle atrophy during immobilization (Selsby and Dodd 2005; Tamura et al. 2015) or a faster recovery in muscle mass during post-immobilization (Selsby et al. 2007). However, the results are equivocal with regards to active participants (Hawley et al. 2018). Some studies have shown increased torque (Goto et al. 2011; Kim et al. 2020; Racinais et al. 2017) and muscle mass (Goto et al. 2011, 2007) following repeated heat exposures, while others have reported no added benefit of heat exposure on training-induced increases in maximal torque and muscle mass (Stadnyk et al. 2018), or no increase in work during repeated contractions or in muscle mass amongst healthy participants not undergoing resistance training nor immobilization (Kim et al. 2020). Thus, the current data showing no effects of heat therapy

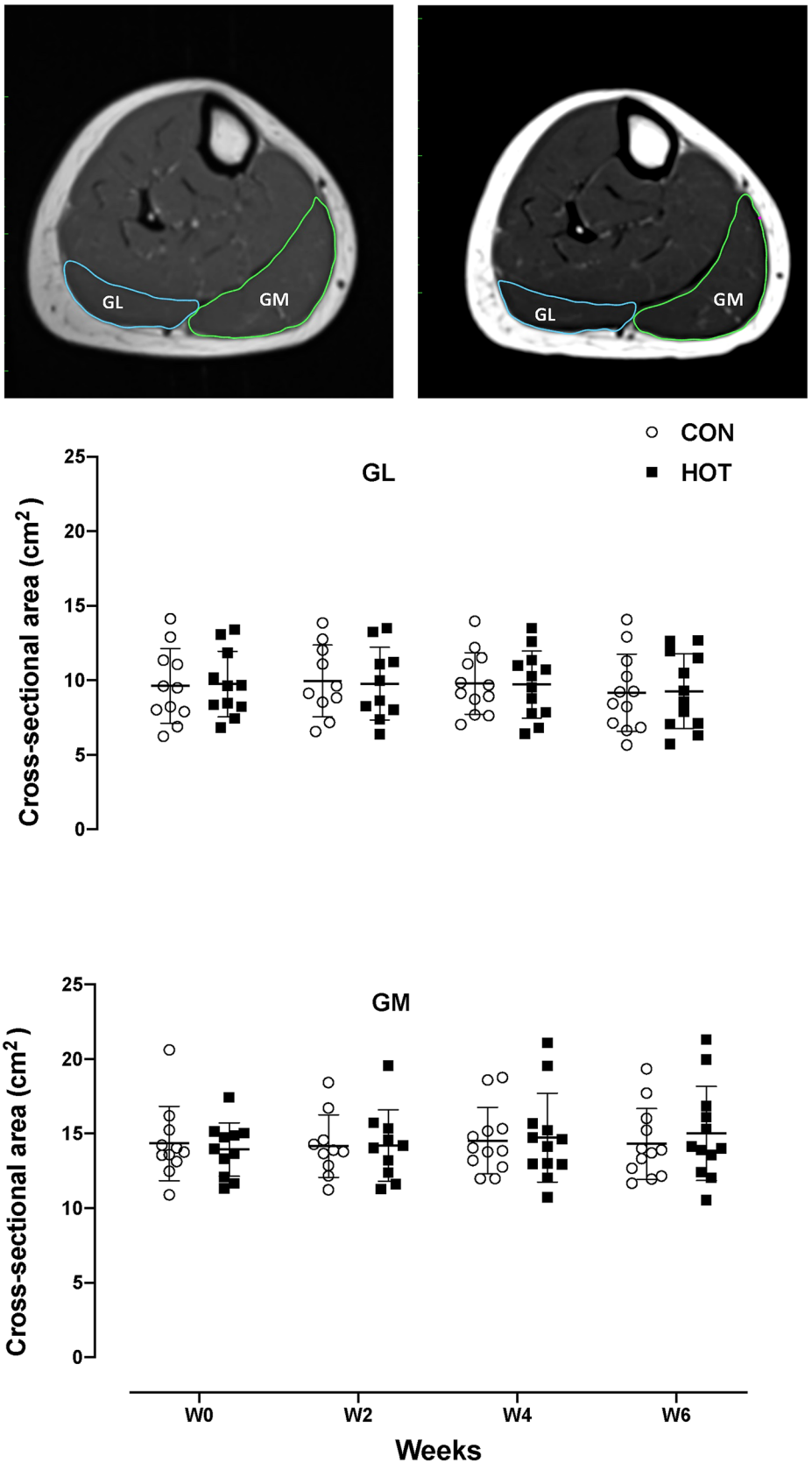

Fig. 3 Top images: Representative images of magnetic resonance imaging obtained from one subject before and after 6 weeks of heat therapy. Bottom graphs: Individual and mean (SD) cross sectional area of the lateral (GL) and medial (GM) gastrocnemius muscles of the control (CON) and heated leg (HOT) before (W0) and after 2, 4 and 6 weeks of localized heat exposures (W2, W4, W6)

Table 3 Muscle thickness, pennation angle and fascial length in the control (CON) and heated leg (HOT) across 6 weeks of passive heat therapy

		W0	W2	W4	W6
Muscle thickness (cm)	CON	1.8 ± 0.2	1.9 ± 0.2	1.8 ± 0.2	1.9 ± 0.2
	HOT	1.8 ± 0.3	1.9 ± 0.2	1.9 ± 0.2	1.9 ± 0.2
Pennation angle (°)	CON	20.3 ± 1.8	20.2 ± 1.5	20.2 ± 1.3	20.9 ± 1.8
	HOT	20.4 ± 2.0	21.1 ± 1.4	21.0 ± 1.8	21.3 ± 1.9
Fascicle length (cm)	CON	5.5 ± 0.5	5.5 ± 0.5	5.5 ± 0.5	5.4 ± 0.4
	HOT	5.5 ± 0.6	5.6 ± 0.6	5.4 ± 0.5	5.5 ± 0.5

Values are means (SD), W0, W2, W4, W6: test before and after 2, 4 and 6 weeks of intervention, respectively

on muscle torque, contractile and hypertrophic responses in active participants, strongly suggest that the effect of local heat therapy may not be additive to mechanical stimulus.

Dose–response relationship

Contrary to the current data, Racinais et al. (2017) reported that 11 days of passive heat exposures improved muscle torque and contractile properties, despite comparable participant characteristics (i.e., active participants maintaining their training routine) and similar testing measures (i.e., electrically evoked twitch and iMVC). However, a major difference may be the use of whole-body heating (Racinais et al. 2017), compared with the local heating modality in the current study. This suggests an effect of heating dose on the magnitude of response. In support, Ihsan et al. (2020) recently reported that 1 h of whole-body heat stress improved anabolic signaling (Akt/mTOR), mitochondrial and cyto-protective signaling (HSP), and inhibited the activity of FOXO transcription factors, whereas 1 h of localized heating failed to induce similar responses. Although not significant, it is of note that muscle temperatures tended to be higher following whole-body (38.8 °C) than local heating (38.1 °C) in this previous study.

Even among localized heat exposures, different techniques may affect muscle temperature differently. Microwave diathermy has been shown to increase muscle temperatures by ~ 7 °C (Nosaka et al. 2007), whereas heat pads and hot water immersion (44 °C for 45 min) increased muscle temperature by ~ 2–3 °C (Goto et al. 2007; Skurvydas et al. 2008). In the current study, the heat pads increased muscle temperature by 4.6 ± 1.2 °C. This modality was selected following pilot trials assessing muscle temperature changes. Moreover, previous studies using a similar modality have reported an increase in muscle torque and CSA after 10 weeks of treatment (Goto et al. 2011, 2007). Given that heat-pads are a simple method, easily available, and do not require extensive procedures or expensive equipment, we aimed to investigate their benefits for muscle function. For example, Paulauskas et al. (2020) recently showed that localized heat pad may acutely improve plantar flexion/dorsiflexion peak torque and rate of torque development on older adults. However, despite the elevation in muscle temperature, the current data do not demonstrate any chronic adaptations in muscle function after 2, 4 or 6 weeks of repeated application, suggesting that the dose was insufficient to induce a clinically meaningful adaptation in active participants. Indeed, the muscle temperature in the heated leg was ~ 37.6 °C, which may not be sufficient to induce heating benefits (Goto et al. 2005). Muscle temperature is an essential factor that mediates the impact of heating through its effects on heat shock protein expression (Naito et al. 2012) and cellular signaling of protein synthesis (Kakigi et al. 2011; Yoshihara et al. 2013). A slight temperature difference may, therefore, influence the activation of the hypertrophic pathways (Goto et al. 2005; Uehara et al. 2004; Kojima et al. 2007).

Moreover, it cannot be ruled out that a longer intervention would have induced an increase in strength. However, this seems unlikely given the absence of any trend on any variables after 6 weeks. Indeed, while Kim et al. (2020) implemented a 8-week intervention, their results showed an increase in torque after 4 weeks, with no further increase after 8 weeks. In addition, another study showed an increase in torque after 11 days of passive heat therapy in the same muscle group examined in the current study (Racinais et al. 2017).

Thus, current data with regards to the literature indicate that a stronger dose of heat therapy (such as whole-body heating) may more likely result in a beneficial outcome in active participants. Yet, the effect of time on iMVC may suggest a cross over effect from the heated to the control leg. However, as the heating procedures was localized to a small area, it was unlikely to induce contra-lateral adaptations. Indeed, there was no effect of time on muscle contractility parameters, and Ihsan et al. (2020) recently showed that localized heating of a single leg did not increase muscle temperature or protein expression in the opposite leg.

Experimental consideration and perspectives

The current experiment was conducted on the plantar flexors as we previously demonstrated that passive whole-body heat exposure (11 days, 1 h per day) improved contractile function in this muscle group (Racinais et al. 2017). Moreover, ankle injuries are one of the most frequent sport-related injuries, accounting for almost a quarter of all injuries in US high-school athletes (Nelson et al. 2007), leading to a rapid plantar flexor muscle atrophy during the first week of immobilization (Stevens et al. 2004). The test/retest correlation for this muscle group between W0 and W2 on the control leg (i.e. where no changes were expected) was 0.93 for iMVC, and 0.91–0.96 for GM and GL CSA.

Whilst the current study did not show an effect of local heating in active humans, it does not imply that local heating may not be beneficial for sedentary or clinical populations, or that a stronger dose resulting in higher muscle temperatures or whole-body heating stimulus would not benefit trained/active individuals. Given that the application of heat therapy to modulate skeletal muscle atrophy/hypertrophy responses is relatively new, future studies should determine the optimal balance between modalities, duration, intensity and frequency of treatment to determine the benefits of heat therapy in different populations.

Conclusion

The current data showed no improvements in isometric, concentric or eccentric torque following 6 weeks of daily local muscle heating in active humans. There were also no structural changes nor changes in contractile properties. These results complement the previous literature showing that local heating may benefit immobilized humans and that whole-body heating may benefit active humans by showing that localized heating was not a potent stimulus for muscle adaptations in active humans. Taken together, this suggests a dose–response relationship where the potential benefits of heating depend on other stimulus received by the participant along the heating dose.

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Author contributions SR conceived the experiments. ML, MI, CT and SR designed the experiments. ML, MI, BF, TS, MM and SR collected data. ML, BF, MA and SR analyzed data. ML drafted the manuscript. All authors contributed to the final manuscript.

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Compliance with ethical standards

Conflict of interest The authors declare no competing interests, financial or otherwise.

References

Beever R (2010) The effects of repeated thermal therapy on quality of life in patients with type II diabetes mellitus. J Altern Complement Med 16(6):677–681. https://doi.org/10.1089/acm.2009.0358

Bishop KN, Durrant E, Allsen PE, Merrill G (1991) The effect of eccentric strength training at various speeds on concentric strength of the quadriceps and hamstring muscles. J Orthop Sports Phys Ther 13(5):226–230. https://doi.org/10.2519/jospt.1991.13.5.226

Brunt VE, Howard MJ, Francisco MA, Ely BR, Minson CT (2016) Passive heat therapy improves endothelial function, arterial stiffness and blood pressure in sedentary humans. J Physiol 594(18):5329–5342. https://doi.org/10.1113/jp272453

Goto K, Okuyama R, Sugiyama H, Honda M, Kobayashi T, Uehara K, Akema T, Sugiura T, Yamada S, Ohira Y, Yoshioka T (2003) Effects of heat stress and mechanical stretch on protein expression in cultured skeletal muscle cells. Pflugers Arch 447(2):247–253. https://doi.org/10.1007/s00424-003-1177-x

Goto K, Honda M, Kobayashi T, Uehara K, Kojima A, Akema T, Sugiura T, Yamada S, Ohira Y, Yoshioka T (2004) Heat stress facilitates the recovery of atrophied soleus muscle in rat. Jpn J Physiol 54(3):285–293. https://doi.org/10.2170/jjphysiol.54.285

Goto K, Kojima A, Kobayashi T, Uehara K, Morioka S, Naito T, Akema T, Sugiura T, Ohira Y, Yoshioka T (2005) Heat stress as a countermeasure for prevention of muscle atrophy in microgravity environment. Jpn J Aerosp Environ Med 42:51–59

Goto K, Oda H, Morioka S, Naito T, Akema T, Kato H, Fujiya H, Nakajima Y, Sugiura T, Ohira Y, Yoshioka T (2007) Skeletal muscle hypertrophy induced by low-intensity exercise with heat-stress in healthy human subjects. Jpn J Aerosp Environ Med 44:13–16

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 (2011) Responses of muscle mass, strength and gene transcripts to long-term heat stress in healthy human subjects. Eur J Appl Physiol 111(1):17–27. https://doi.org/10.1007/s00421-010-1617-1

Hafen PS, Preece CN, Sorensen JR, Hancock CR, Hyldahl RD (2018) Repeated exposure to heat stress induces mitochondrial adaptation in human skeletal muscle. J Appl Physiol (1985) 125(5):1447–1455. https://doi.org/10.1152/japplphysiol.00383.2018

Hafen PS, Abbott K, Bowden J, Lopiano R, Hancock CR, Hyldahl RD (2019) Daily heat treatment maintains mitochondrial function and attenuates atrophy in human skeletal muscle subjected to immobilization. J Appl Physiol (1985) 127(1):47–57. https://doi.org/10.1152/japplphysiol.01098.2018

Hawley JA, Lundby C, Cotter JD, Burke LM (2018) Maximizing cellular adaptation to endurance exercise in skeletal muscle. Cell Metab 27(5):962–976. https://doi.org/10.1016/j.cmet.2018.04.014

Ihsan M, Deldicque L, Molphy J, Britto F, Cherif A, Racinais S (2020) Skeletal muscle signaling following whole-body and localized heat exposure in humans. Front Physiol 11:839

Jones DA, Rutherford OM, Parker DF (1989) Physiological changes in skeletal muscle as a result of strength training. Q J Exp Physiol

74(3):233–256. https://doi.org/10.1113/expphysiol.1989.sp003268

Kakigi R, Naito H, Ogura Y, Kobayashi H, Saga N, Ichinoseki-Sekine N, Yoshihara T, Katamoto S (2011) Heat stress enhances mTOR signaling after resistance exercise in human skeletal muscle. J Physiol Sci 61(2):131–140. https://doi.org/10.1007/s12576-010-0130-y

Kim K, Reid BA, Casey CA, Bender BE, Ro B, Song Q, Trewin AJ, Petersen AC, Kuang S, Gavin TP, Roseguini BT (2020) Effects of repeated local heat therapy on skeletal muscle structure and function in humans. J Appl Physiol (1985) 128(3):483–492. https://doi.org/10.1152/japplphysiol.00701.2019

Kitai TA, Sale DG (1989) Specificity of joint angle in isometric training. Eur J Appl Physiol Occup Physiol 58(7):744–748. https://doi.org/10.1007/bf00637386

Kojima A, Goto K, Morioka S, Naito T, Akema T, Fujiya H, Sugiura T, Ohira Y, Beppu M, Aoki H, Yoshioka T (2007) Heat stress facilitates the regeneration of injured skeletal muscle in rats. J Orthop Sci 12(1):74–82. https://doi.org/10.1007/s00776-006-1083-0

Kumagai K, Abe T, Brechue WF, Ryushi T, Takano S, Mizuno M (2000) Sprint performance is related to muscle fascicle length in male 100-m sprinters. J Appl Physiol (1985) 88(3):811–816. https://doi.org/10.1152/jappl.2000.88.3.811

Laukkanen T, Khan H, Zaccardi F, Laukkanen JA (2015) Association between sauna bathing and fatal cardiovascular and all-cause mortality events. JAMA Intern Med 175(4):542–548. https://doi.org/10.1001/jamainternmed.2014.8187

Naito H, Yoshihara T, Kakigi R, Ichinoseki-Sekine N, Tsuzuki T (2012) Heat stress-induced changes in skeletal muscle: heat shock proteins and cell signaling transduction. J Phys Fit Sports Med 1(1):125–131

Nelson AJ, Collins CL, Yard EE, Fields SK, Comstock RD (2007) Ankle injuries among United States high school sports athletes, 2005–2006. J Athl Train 42(3):381–387

Nosaka K, Muthalib M, Lavender A, Laursen PB (2007) Attenuation of muscle damage by preconditioning with muscle hyperthermia 1-day prior to eccentric exercise. Eur J Appl Physiol 99(2):183–192. https://doi.org/10.1007/s00421-006-0331-5

Paulauskas H, Baranauskiene N, Wang J, Mikucioniene D, Eimantas N, Brazaitis M (2020) Local knee heating increases spinal and supraspinal excitability and enhances plantar flexion and dorsiflexion torque production of the ankle in older adults. Eur J Appl Physiol. https://doi.org/10.1007/s00421-020-04449-8

Racinais S, Maffiuletti NA, Girard O (2013) M-wave, H- and V-reflex recruitment curves during maximal voluntary contraction. J Clin Neurophysiol 30(4):415–421. https://doi.org/10.1097/WNP.0b013e31829ddcf1

Racinais S, Wilson MG, Periard JD (2017) Passive heat acclimation improves skeletal muscle contractility in humans. Am J Physiol Regul Integr Comp Physiol 312(1):R101-r107. https://doi.org/10.1152/ajpregu.00431.2016

Seger JY, Arvidsson B, Thorstensson A (1998) Specific effects of eccentric and concentric training on muscle strength and morphology in humans. Eur J Appl Physiol Occup Physiol 79(1):49–57. https://doi.org/10.1007/s004210050472

Selsby JT, Dodd SL (2005) Heat treatment reduces oxidative stress and protects muscle mass during immobilization. Am J Physiol Regul Integr Comp Physiol 289(1):R134-139. https://doi.org/10.1152/ajpregu.00497.2004

Selsby JT, Rother S, Tsuda S, Pracash O, Quindry J, Dodd SL (2007) Intermittent hyperthermia enhances skeletal muscle regrowth and attenuates oxidative damage following reloading. J Appl Physiol (1985) 102(4):1702–1707. https://doi.org/10.1152/japplphysiol.00722.2006

Skurvydas A, Kamandulis S, Stanislovaitis A, Streckis V, Mamkus G, Drazdauskas A (2008) Leg immersion in warm water, stretch-shortening exercise, and exercise-induced muscle damage. J Athl Train 43(6):592–599. https://doi.org/10.4085/1062-6050-43.6.592

Sobajima M, Nozawa T, Ihori H, Shida T, Ohori T, Suzuki T, Matsuki A, Yasumura S, Inoue H (2013) Repeated sauna therapy improves myocardial perfusion in patients with chronically occluded coronary artery-related ischemia. Int J Cardiol 167(1):237–243. https://doi.org/10.1016/j.ijcard.2011.12.064

Sobajima M, Nozawa T, Fukui Y, Ihori H, Ohori T, Fujii N, Inoue H (2015) Waon therapy improves quality of life as well as cardiac function and exercise capacity in patients with chronic heart failure. Int Heart J 56(2):203–208. https://doi.org/10.1536/ihj.14-266

Stadnyk AMJ, Rehrer NJ, Handcock PJ, Meredith-Jones KA, Cotter JD (2018) No clear benefit of muscle heating on hypertrophy and strength with resistance training. Temperature (Austin) 5(2):175–183. https://doi.org/10.1080/23328940.2017.1391366

Stevens JE, Walter GA, Okereke E, Scarborough MT, Esterhai JL, George SZ, Kelley MJ, Tillman SM, Gibbs JD, Elliott MA, Frimel TN, Gibbs CP, Vandenborne K (2004) Muscle adaptations with immobilization and rehabilitation after ankle fracture. Med Sci Sports Exerc 36(10):1695–1701. https://doi.org/10.1249/01.Mss.0000142407.25188.05

Tamura Y, Kitaoka Y, Matsunaga Y, Hoshino D, Hatta H (2015) Daily heat stress treatment rescues denervation-activated mitochondrial clearance and atrophy in skeletal muscle. J Physiol 593(12):2707–2720. https://doi.org/10.1113/jp270093

Tomberlin JP, Basford JR, Schwen EE, Orte PA, Scott SC, Laughman RK, Ilstrup DM (1991) Comparative study of isokinetic eccentric and concentric quadriceps training. J Orthop Sports Phys Ther 14(1):31–36. https://doi.org/10.2519/jospt.1991.14.1.31

Uehara K, Goto K, Kobayashi T, Kojima A, Akema T, Sugiura T, Yamada S, Ohira Y, Yoshioka T, Aoki H (2004) Heat-stress enhances proliferative potential in rat soleus muscle. Jpn J Physiol 54(3):263–271. https://doi.org/10.2170/jjphysiol.54.263

Yoshihara T, Naito H, Kakigi R, Ichinoseki-Sekine N, Ogura Y, Sugiura T, Katamoto S (2013) Heat stress activates the Akt/mTOR signalling pathway in rat skeletal muscle. Acta Physiol (Oxf) 207(2):416–426. https://doi.org/10.1111/apha.12040