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Research article

Thermal Infrared Imaging Can Differentiate Skin Temperature Changes Associated With Intense Single Leg Exercise, But Not With Delayed Onset of Muscle Soreness

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Abstract

Muscle damage and soreness associated with increased exercise training loads or unaccustomed activity can be debilitating and impact the quality of subsequent activity/performance. Current techniques to assess muscle soreness are either time consuming, invasive or subjective. Infrared thermography has been identified as a quick, non-invasive, portable and athlete friendly method of assessing skin temperature. This study assessed the capability of thermal infrared imaging to detect skin temperature changes that may accompany the inflammatory response associated with delayed onset muscular soreness (DOMS). Eight recreationally trained participants (age 25 ± 3 years, mass 74.9 ± 13.6 kg, training minutes 296 ± 175 min·wk^{-1}) completed 6 sets of 25 maximal concentric/eccentric contractions of the right knee flexors/extensors on a dynamometer to induce muscle damage and DOMS. The left knee extensors acted as a non-exercise control. Neuromuscular performance, subjective pain assessment and infrared thermography were undertaken at baseline, 24 and 48 hr post the DOMS-inducing exercise protocol. Data were analysed using Bayesian hierarchical regression and Cohen's *d* was also calculated. Maximal voluntary contraction torque was statistically lower at 24 hr (d = -0.70) and 48 hr (d = -0.52) compared to baseline, after the DOMS-inducing exercise protocol. These neuromuscular impairments coincided with statistically higher ratings of muscle soreness at 24 hr (d = 0.96) and 48 hr (d = 0.48). After adjusting for ambient temperature, anterior thigh skin temperature was statistically elevated at 24 hr, but not 48 hr, compared with baseline, in both the exercised and non-exercised leg. Thigh temperature was not different statistically between legs at these time points. Infrared imaging was able to detect elevations in skin temperature, at 24 hrs after the DOMS inducing exercise protocol, in both the exercised and non-exercised thigh. Elevations in the skin temperature of both thighs, potentially identifies a systemic inflammatory response occurring at 24 hr after the DOMS-inducing exercise protocol.

Key words: Infrared thermal imaging, skin temperature, muscle damage, muscle soreness.

Introduction

Delayed onset muscle soreness (DOMS) is common following unaccustomed exercise bouts. Symptoms can range from muscle tenderness to severe debilitating soreness. This soreness leads to functional impairment, altered joint kinematics and recruitment patterns, reductions in strength and power and subsequently increases in injury risk (MacIntyre et al., 1995). The time-course of these symptoms and related discomfort increases within the first 24 hour (hr) following the termination of the exercise, and peaks between 24 to 72 hr following the exercise bout (MacIntyre et al., 1995). Current techniques employed to assess DOMS consist of muscle force assessment (Brown et al., 1997; Paddon-Jones and Quigley, 1997), blood assays (Warren et al., 1999), muscle biopsies, MRI imaging (Agten et al., 2017) or subjective scales (Lau et al., 2013). An accurate, non-invasive, physically undemanding and objective method to assess DOMS could help monitor training loads, prevent injuries, and optimise athletic performance.

The acute inflammation that accompanies DOMS (Pournot et al., 2011), could manifest as temperature variations of the skin immediately superficial to the damaged muscle. Fluctuations in skin temperature may provide an indication of the presence of underlying pathology. These alterations can be detected as whole-body skin temperature changes (e.g., fever, or as localised inflammation). Localised skin temperature measurement has been used to monitor and detect localised inflammation associated with rheumatoid arthritis, osteoarthritis, allergies, frozen shoulder and following knee replacements (Ring and Ammer, 2012). Infrared thermography has been identified as a quick, non-invasive, portable and patient/athlete friendly method of assessing skin temperature (Costello et al., 2013).

Therefore, the primary aim of this investigation was to examine the capability of thermal infrared imaging to detect skin temperature changes that accompany delayed onset muscular soreness. It was hypothesised that the skin immediately superficial to the exercised/damaged muscle would show elevations in temperature at 24 and 48 hours after exercise and these elevations would not be apparent in the non-damaged control limb. A secondary aim was to determine if thermal infrared imaging of the skin could detect acute changes in muscle activity associated with a DOMS-inducing exercise protocol. It was hypothesised that the skin immediately superficial to the exercised muscle would show elevations in temperature during the activity, while the temperature would remain unchanged in the non-exercised control limb.

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Methods

Participants

Eight recreationally-active males took part in this study and their characteristics were as follows, mean ± standard deviation (SD): age 25 ± 3 years, height 1.74 ± 0.10 m, mass 74.9 ± 13.6 kg, training sessions 4 ± 1 sessions·wk^{-1}, training minutes (min) 296 ± 175 min·wk^{-1}. At the time of the investigation, participants were free of injury and illness, and were not taking any vasodilation or thermoregulatory altering medication (Exercise and Sports Science Australia, Adult Pre-Exercise Screening Tool). Before participation, written informed consent was obtained. The study was approved by the University Human Research Ethics Committee (UHREC #1700000140).

Experimental overview

The study followed a within-participant design, requiring volunteers to visit the laboratory on four occasions. The initial visit (5–7 d before visit two) involved a comprehensive neuromuscular testing familiarisation. The second visit involved resting thermal images of the right and left anterior thighs, and maximal voluntary contraction (MVC) testing before and after an intense exercise protocol designed to induce acute muscle damage and DOMS. For the purposes of this study, reductions in MVC torque and alterations in peripheral muscle properties, along with subjective ratings of soreness, were used to infer the presence of DOMS. Visits 3–4 involved a thermal image, and an MVC test. Figure 1 portrays the experimental design for visits 2–4. Testing was balanced for morning-afternoon, and within a participant, all testing was performed at the same time of day (±1 hr). The study was conducted during the Australian winter months (June–July).

Initial testing session

Height and nude body mass were recorded, and participants completed the pre-exercise screening questionnaire (Exercise and Sports Science Australia Adult Pre-Exercise Screen Tool). After a standardised warm-up (WU; see neuromuscular section), individuals completed multiple-sets of 5 s isometric MVC's during which twitch interpolation was applied. Participants were considered familiarised after achieving a plateau in MVC torque for a full set (5 x 5 s) of contractions. On average familiarisation took 7 sets (range 3–9). During the initial visit, participants were also familiarised to the perceptual measures—perceived soreness, session rating of perceived exertion (session-RPE) and the modified profile of mood states 'POMS' questionnaire. Perceived soreness was rated from 0 'no soreness' to 10 'extremely sore' on a visual analogue scale. The modified POMS comprised six items (active, energetic, restless, fatigued, exhausted, and alertness). Each item was rated on a 1–5 scale (0.5 increments), ranging from 1 'low' to 5 'high'. Items were summed, providing a global indication of 'mood', with a higher score reflecting better mood. A session-RPE was collected 10 min after exercise (Foster et al., 2001).

Participants were given specific instructions for the days leading up to their first testing session so to ensure adequate preparation of thermal image skin sites. Namely, (a) avoid prolonged sun exposure five days prior to testing to prevent sun burn; (b) if applicable, remove hair (Togawa and Saito, 1994) from the anterior and posterior aspects of both thighs 36 hr before testing to prevent inflammation and/or skin surface damage (Merla et al., 2010); (c) avoid exercise, caffeine and alcohol in the 24 hr prior to testing (Moreira et al., 2017); and (d) avoid hot showers, ointments and cosmetics on each testing day.

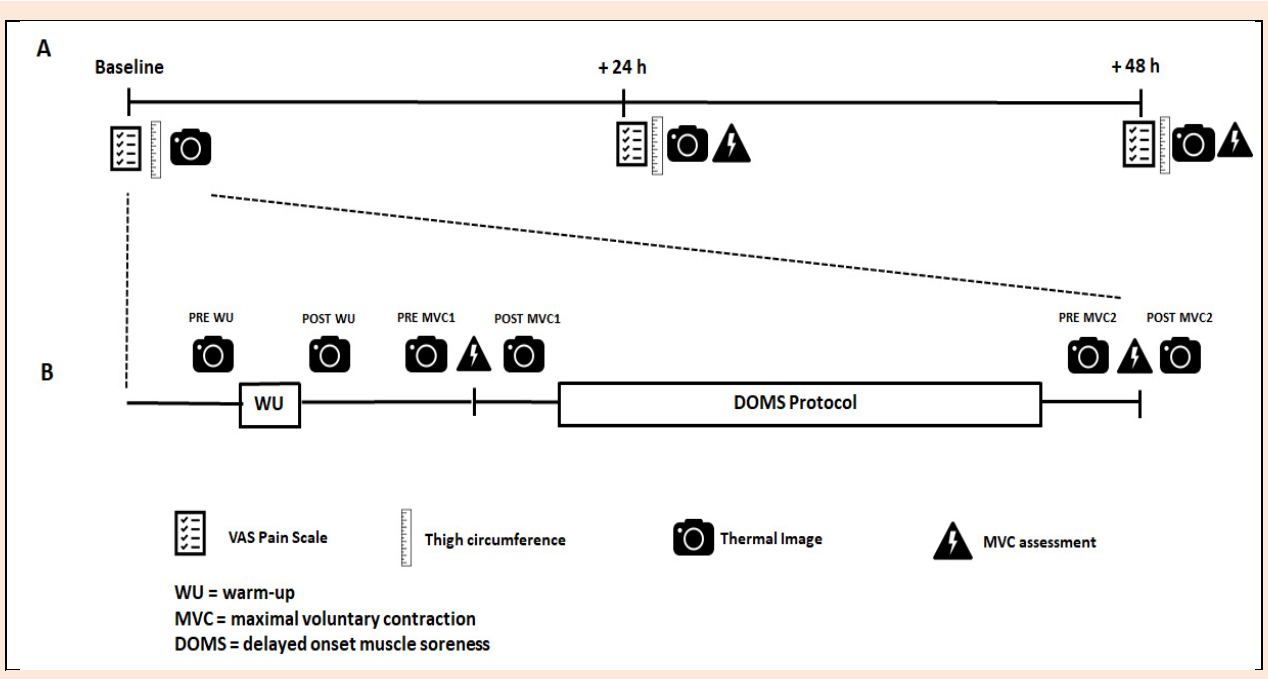

Figure 1. Experimental design. Panel A addresses the aim to examine the capability of thermal infrared imaging to detect skin temperature changes that accompany delayed onset muscular soreness. Panel B addresses the aim to determine if thermal infrared imaging of the skin could detect acute changes in muscle activity associated with a DOMS-inducing exercise protocol.

Thermal images

Two thermal infrared cameras were utilised to assess resting (A305sc, FLIR Systems, Wilsonville, Orego, USA) and exercising (PI450, Optris Gmbh, Berlin, Germany) skin temperature. Measurements were undertaken in temperature-controlled, LED lit rooms without the existence of electric heat generators, wind drafts or external radiation sources. Before the resting images being collected the participant rested for 20 min in a seated position (Moreira et al., 2017) in order to acclimate to the temperature of the room (mean ± SD; 22.7 ± 0.3 °C, 50 ± 6% RH). Resting thermal images, with the FLIR camera (320 x 240 pixel resolution), were then conducted with camera positioning (1.1-1.4m; relative to participant's height), stabilisation, emissivity and image processing as previously reported (Bach et al., 2015). On average 13615 (SD 2848) pixels (data points) comprised each resting region of interest. The exercising thermal images were conducted with the Optris camera (384 x 288 pixel resolution) mounted on a portal frame, downward looking and parallel with the anterior thigh regions while the participant was seated on the dynamometer. The distance between the camera and the anterior surface of the thigh was set to 1.2 m to ensure both right and left thighs were in the field of view of the camera. Data sampling and image processing were as previously reported (Moghadam, 2015; Vidas et al., 2015). Briefly, this involved a quadrangle region of interest around the thigh being extracted. A false colourised thermal image was then displayed to allow for a manual region of interest to be selected. A mask was then generated using Gaussian blurring with the raw image to generate an unsharpened mask. The region of interest and mask were combined and then applied to the raw thermal image to extract solely the data of interest. The numeric mean of this data was then calculated. On average 3500 (SD 700) pixels (data points) comprised each exercising region of interest.

Neuromuscular function

Neuromuscular function was assessed via maximal voluntary contraction (MVC) and evoked twitch properties of the right knee extensors using a Biodex isokinetic dynamometer (Systems 3, Biodex Medical Systems, New York, USA). Participants were seated in an upright position, chair backrest adjusted to 95° from the horizontal plane, and tightly secured with waist, shoulder, hip and thigh straps. The lateral epicondyle of the femur was aligned with the axis of rotation of the dynamometer, and the right knee was positioned at 90°, with 0° being full extension. The lower leg was firmly strapped to the lever arm, approximately 2 cm above the lateral malleolus of the ankle. Before testing, participants completed 15 isometric knee extension WU contractions, 5 at 40% perceived maximal effort, 5 at 60%, 3 at 80% and 2 at 90%, with 10 s rest between each contraction.

The use of twitch interpolation was to assist in indirectly distinguishing whether reductions in MVC torque were related to central perturbations, or peripheral muscle factors (Shield and Zhou, 2004). Muscle activation of the right knee extensors was achieved by percutaneous stimulation of the femoral nerve using a self-adhesive electrode (anode, 3.2 cm diameter; Pals, Axelgaard Manufacturing Co. Ltd., Fallbrook, USA). A second electrode was placed on the border of the gluteal fold (cathode, 5 x 9 cm; Pals, Axelgaard Manufacturing Co. Ltd., Fallbrook, USA). During MVC, a single square-wave pulse width of 100 µs (400 V with a current of 400–700 mA) was delivered via a stimulator (DS7AH; Digitimer Ltd., Welwyn Garden City, England) at 120% of maximal peak twitch torque. The required current was determined via a twitch ramp procedure commencing at 50 mA, thereby increasing 50 mA every 30 s until a plateau in peak (evoked) twitch torque was achieved. Within ~2 s following MVC a second stimulus was delivered to examine muscle contractile properties (Shield and Zhou, 2004). To maximise voluntary activation and enhance motivation, strong verbal encouragement and visual force feedback was provided during MVC's (Shield and Zhou, 2004).

Neuromuscular data were sampled at 1,000 Hz and recorded into LabChart (LabChart 8.0; AD Instruments, Sydney, Australia) via a PowerLab system (16-bit PowerLab 26T; AD Instruments, Sydney, Australia). Maximal voluntary torque was considered the mean value in the 25 ms period preceding the electric stimuli. Superimposed torque was considered the peak value in the 100 ms after the stimuli. The level of voluntary activation (VA) was determined for each MVC using the twitch interpolation technique, with VA calculated as: $((1 - a/b) \cdot 100)$, where 'a' is the superimposed twitch, and 'b' the potentiated twitch (Shield and Zhou, 2004). MVC repetitions were excluded from analysis if: (1) no plateau prior to stimulation was achieved; (2) the superimposed stimulus was delivered at a sub-maximal force; or (3) stimulation occurred at a non-maximal effort (Shield and Zhou, 2004). Peak twitch torque, rate of torque development (RTD), contraction time, and half-relaxation time were determined for each twitch response. Alterations in these properties were used to infer acute muscular fatigue. In our laboratory, following familiarisation, the between-day intraclass correlation coefficient (ICC; 2, 1) of these assessments is: MVC torque = 0.94, VA = 0.94, peak twitch torque = 0.97, contraction time = 0.94, RTD = 0.90 and half-relaxation time = 0.98, respectively.

Exercise protocol

Following the pre-exercise MVC test (MVC 1), participants undertook an intense single-leg exercise protocol consisting of a series of maximal concentric (CON) and eccentric (CON) contractions of the right knee extensors. The left knee extensors acted as a non-exercise control. Participants were seated upright and secured as per the MVC testing. The protocol involved 6 sets of 25 maximal CON/ECC contractions at an angular velocity of 60 (CON) and 120°·s^{-1} (ECC), performed within a range of 15° to 80° knee flexion, with 0° being full knee extension. A 5 min rest period separated each set. A similar exercise protocol has previously been shown to induce acute muscle fatigue and DOMS in resistance trained male athletes (Pointon et al., 2011). Participants were instructed to provide maximal

effort across the range of each CON/EEC contraction. Loud verbal encouragement was provided throughout, and visual force feedback was displayed on a computer monitor situated 1.5 m in front of the dynamometer. Five min after protocol completion post-exercise MVC (MVC 2) testing was performed, and 10 min after exercise, votes of session-RPE and soreness were collected.

Follow-up testing

Participants returned to the laboratory 24 hr and 48 hr following the baseline testing session. Perceived muscle soreness and POMS were collected, and right thigh girth was assessed (F10-02DM, KDS, Malaysia). After a 20 min acclimation period, thermal images of both thighs were conducted before undertaking the MVC protocol. Approximately 10 min after MVC, a session-RPE was collected.

Data analysis

The analyses were undertaken in R (Version 3.4.4). Bayesian hierarchical regression was used to model skin temperature, neuromuscular variables, indoor temperature, mood and thigh girth. Models were implemented using the packages 'rjags' and 'R2jags' (Lunn et al., 2009; Plummer et al., 2006). Models included time (neuromuscular variables, ambient temperature, mood, thigh girth) or time, leg and time x leg (skin temperature) as fixed factors. All models also included a random intercept for each participant to account for the correlation between repeated observations on an individual. When skin temperature was the response variable, indoor temperature was included as a standardised covariate. Markov chain Monte Carlo (MCMC) methods were used to generate posterior estimates (50,000 MCMC iterations, a 1,000-iteration burn-in, thinned by a factor of 10). A Normal (mean 0, precision 0.001) prior distribution was utilised for each regression coefficient and a Gamma (shape 0.01, scale 0.01) prior for the variance parameters.

Perceived soreness ratings and session-RPE were modelled with a beta-response distribution, using the 'zoib' package (Liu and Kong, 2015). For these models, time was included as a fixed factor, and participant as a random effect variable. Posterior estimates were generated via MCMC procedures (2 independent chains, 10,200 MCMC iterations, a 200 iteration burn-in, and thinned by a factor of 50). A Normal (mean 0, precision 0.001) prior distribution was used for the regression coefficients and a Uniform (mean 0, SD 20) prior distribution for the SD of the random effects.

Posterior estimates are reported as the mean or mean difference (MD) and 95% credible interval (CI). Cohen's *d* (and 95% CI) and a Bayes factor (BF) were computed for each pairwise comparison using the 'BayesFactor' package (Morey and Rouder, 2018). Values of *d* were interpreted as small 0.20–0.49, medium 0.50–0.79 and large ≥0.80 (Cohen, 1988). Bayes factor values were used as a measure of the strength of evidence in favour of the null (BF_{10} <1) or alternate (BF_{10} >1) hypothesis (Jarosz and Wiley, 2014). Values further away from 1 provide greater evidence. Finally, for resting anterior thigh temperature, the posterior probability that the absolute difference in skin temperature exceeded 0.5 °C was also calculated, denoted as Pr T_{SK} >0.5 °C or Pr T_{SK} < -0.5 °C, depending on the direction of the difference (Mengersen et al., 2016).

The convergence of the MCMC to the posterior distribution was visually assessed via trace plots. Posterior predictive checks were performed to assess the suitability of all chosen models. Evidence of a statistical effect or difference was accepted when the 95% CI of a regression coefficient or MD did not cross zero.

Results

Ambient temperature

There was an effect of time ($\beta_{24\ hr}$ [95% CI] = 0.31 [0.04, 0.59]; $\beta_{48\ hr}$ = 0.37 [0.10, 0.66]) on indoor temperature (Table 1). Indoor temperature was statistically higher at 24 hr (MD [95% CI] = 0.3 °C [0.0, 0.6]; *d* [95% CI] = 0.67 [-0.06, 1.47]; BF_{10} = 1.92) and 48 hr compared to baseline (MD = 0.4 °C [0.1, 0.7]; *d* = 0.85 [0.06, 1.73; BF_{10} = 3.82]). Indoor temperature was not statistically different between 24 hr and 48 hr.

Baseline measures

Skin temperature: There were effects for time ($\beta_{24\ hr}$ [95% CI] = 0.34 [0.08, 0.62]) and the ambient temperature covariate (β = 0.16 [0.02, 0.31]) on resting anterior thigh temperature. There was no evidence of a time x leg effect, indicating that resting thigh temperatures were not statistically different between legs at any time (Figure 2). There was, however, evidence that both RIGHT and LEFT thigh temperatures were statistically higher at 24 hr compared to baseline (MD [95% CI] = 0.33 °C [0.13, 0.53]; *d* [95% CI] = 1.05 [0.43, 1.72]; BF_{10} = 103.82; Pr T_{SK} >0.5 °C = .049; Figure 2) and 48 hr (MD = 0.28 °C [0.12, 0.45]; *d* = 0.67 [0.14, 1.22]; BF_{10} = 6.66; Pr T_{SK} >0.5 °C = .006; Figure 2). There was no evidence that anterior thigh temperatures were statistically different between baseline and 48 hr.

Table 1. Posterior mean (95% credible interval) environment, neuromuscular and perceptual variables pre-exercise at baseline, and before maximal voluntary contraction (MVC) at 24 hr and 48 hr.

Variable	Variable	Baseline	24 hr	48 hr
Environment	Indoor ambient temperature (°C)	22.4 [22.1, 22.7]	**22.7 [22.4, 23.0]**[a]	**22.8 [22.5, 23.0]**[a]
Neuromuscular	MVC torque (Nm)	227 [194, 259]	**202 [171, 234]**[a]	**208 [176, 239]**[a]
	Voluntary activation (%)	93.6 [90.1, 96.9]	93.7 [90.3, 97.0]	93.1 [89.7, 96.6]
	Peak twitch torque (Nm)	72 [63, 81]	**66 [56, 75]**[a]	69 [60, 78]
	Rate of torque development ($Nm \cdot ms^{-1}$)	794 [712, 877]	780 [696, 859]	848 [764, 929]
	Contraction time (ms)	164 [143, 184]	**150 [130, 170]**[a]	159 [138, 179]
	Half-relaxation time (ms)	71 [58, 84]	66 [54, 79]	**77 [64, 89]**[b]
Perceptual	Mood (au)	16 [14, 18]	15 [13, 18]	15 [13, 17]
	Soreness (au)	0 [0, 1]	**2 [0, 4]**[a]	**1 [0, 3]**[a]

Statistical differences are bolded, [a] statistically different to baseline, [b] statistically different to 24 hr.

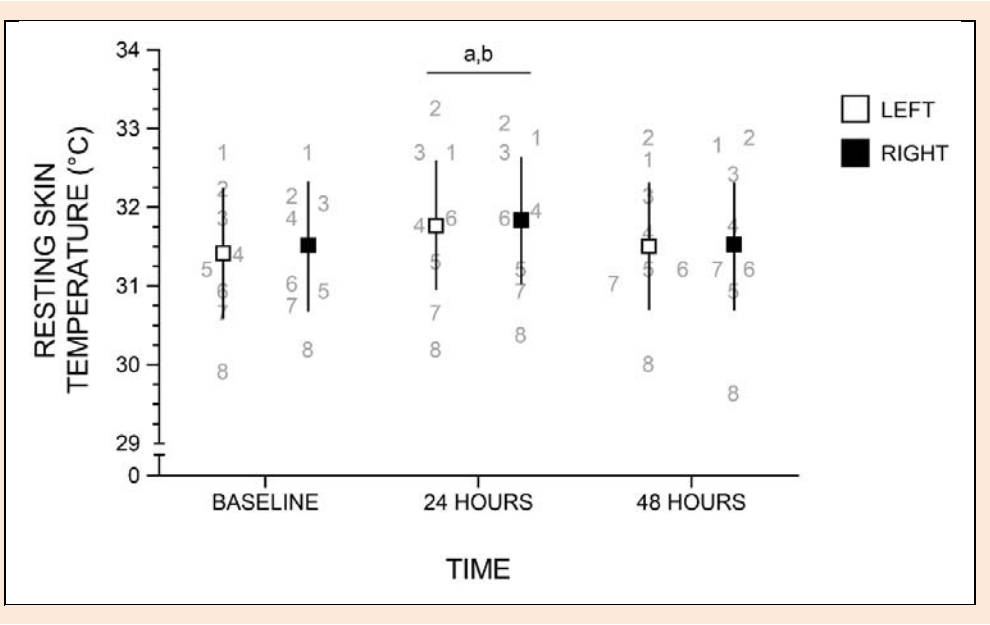

Figure 2. Posterior mean (95% credible interval) of the RIGHT and LEFT anterior thigh skin temperature at baseline, 24 hr and 48 hr. Individual data are shown with numbers, [a] RIGHT and LEFT skin temperature statistically different to baseline, [b] RIGHT and LEFT skin temperature statistically different to 48 hr.

Neuromuscular function: There was an effect of time on MVC torque ($\beta_{24\ hr}$ [95% CI] = -24.7 [-43.9, -5.7]; $\beta_{48\ hr}$ = -19.2 [-38.1, -0.2]). MVC torque was statistically lower at 24 hr compared to baseline (MD [95% CI] = -25 N·m [-44, -6]; *d* [95% CI] = -0.70 [-1.26, -0.16]; BF_{10} = 8.00; Table 1) and possibly at 48 hr compared to baseline (MD = -19 N·m [-38, 0]; *d* = -0.52 [-1.03, -0.03]; BF_{10} = 2.18). There was an effect of time on peak twitch torque ($\beta_{24\ hr}$ = -6.8 [-12.0, -1.5]), contraction time ($\beta_{24\ hr}$ = -13.5 [-22.5, -4.3]) and half-relaxation time ($\beta_{48\ hr}$ = 5.2 [3.9, 13.9]), but not VA or RTD. Peak twitch torque was statistically lower at 24 hr compared to baseline (MD = -7 N·m [-12, -1]; *d* = -0.55 [-1.07, -0.04]; BF_{10} = 2.79). Half-relaxation time was statistically slower at 48 hr compared to 24 hr (MD = 11 ms [2, 19]; *d* = 0.94 [0.34, 1.55]; BF_{10} = 44.34). Contraction time was statistically faster at 24 hr compared to baseline (MD = -14 ms [-22, -4]; *d* = -0.61 [-1.15, -0.08]; BF_{10} = 4.18).

Perceptual measures and girth circumference: There was a time effect on perceived soreness at rest (logit-$\beta_{24\ hr}$ [95% CI] = 2.4 [1.0, 3.8]; logit-$\beta_{48\ hr}$ = 2.2 [0.7, 3.6]). Perceived soreness (Table 1) was statistically higher at 24 hr (MD [95% CI] = 1.5 au [0.4, 3.6]; *d* [95% CI] = 0.96 [0.10, 1.92]) and 48 hr (MD = 1.2 au [0.2, 2.8]; *d* = 0.48 [-0.19, 1.22]) compared to baseline. Perceived soreness was not statistically different between 24 hr and 48 hr (Table 1). Mood scores were not different between any time points (Table 1). Mean [95% CI] session-RPE ratings at 24 and 48 hr after MVC were 6 au [1, 9] and 6 [2, 10], respectively. Session-RPE was not statistically different between 24 and 48 hr. Mean [95% CI] right thigh girths were: baseline 57.6 cm [54.4, 60.8], 24 hr 57.8 [54.6, 61.0], and 48 hr 57.7 [54.5, 60.8]. Thigh girth was not statistically different between any time points.

Before and after exercise on the first testing day

Skin temperature: For anterior thigh temperatures during exercise, there were effects for time ($\beta_{post\ MVC1}$ [95% CI] = -0.40 [-0.69, -0.10]; $\beta_{pre\ MVC2}$ = -1.18 [-1.49, -0.88]; $\beta_{post\ MVC2}$ = -1.31 [-1.61, -1.01]) and leg x time ($\beta_{pre\ MVC1}$ = 0.81 [0.39, 1.23]; $\beta_{post\ MVC1}$ = 1.08 [0.66, 1.50]; $\beta_{pre\ MVC2}$ = 2.58 [2.16, 3.02]; $\beta_{post\ MVC2}$ = 2.43 [2.00, 2.86]), but not the ambient temperature covariate (β = 0.56 [-0.16, 1.30]). As per Figure 3A–B, compared to pre WU, RIGHT temperature was higher post WU (*d* [95% CI] = 1.06 [0.18, 2.05]; BF_{10} = 7.48), pre MVC1 (*d* = 0.78 [0.01, 1.62]; BF_{10} = 2.89), post MVC1 (*d* = 0.87 [0.05, 1.77]; BF_{10} = 3.86), pre MVC2 (*d* = 2.72 [1.04, 4.58]; BF_{10} = 510), and post MVC2 (*d* = 2.15 [0.77, 3.70]; BF_{10} = 154). As per Figure 3A–B, compared to pre WU, LEFT thigh temperature was lower post MVC1 (*d* = -0.86 [-1.78, -0.07]; BF_{10} = 3.92), pre MVC2 (*d* = -3.56 [-5.89, -1.50]; BF_{10} = 2,272) and post MVC2 (*d* = -4.00 [-6.57, -1.74]; BF_{10} = 3,981). The RIGHT temperature was statistically different to LEFT from pre MVC1 onwards (*d* = 2.07 to 8.00; BF_{10} = 137 to 224,343; Figure 3A and 3C).

Neuromuscular function and perceived soreness: There was a time effect on all neuromuscular variables: MVC torque (β [95% CI] = -64.3 [-83.9, -44.9]), VA (β = -7.3 [-9.5, -5.1]), peak twitch torque (β = -34.9 [-40.1, -29.7]), RTD (β = -331.1 [-405.9, -256.3]), contraction time (β = -28.6 [-37.7, -19.2]) and half-relaxation time (β = -16.8 [-25.4, -8.1]). As expected, there were deficits in all neuromuscular variables post-exercise compared to pre (*d* = -0.64 to -3.08; BF_{10} = 5.14 to 7,792,157; Table 2). These changes were indicative of suboptimal function. Perceived soreness before and after exercise was 0 au [0, 0] and 7 [5, 8], respectively. There was a time effect on soreness (β = 5.0 [3.4, 6.4]), with post-exercise ratings higher compared to pre-exercise values (MD [95% CI] = 6 au [5, 8]; *d* [95% CI] = 2.50 [0.92, 4.27]).

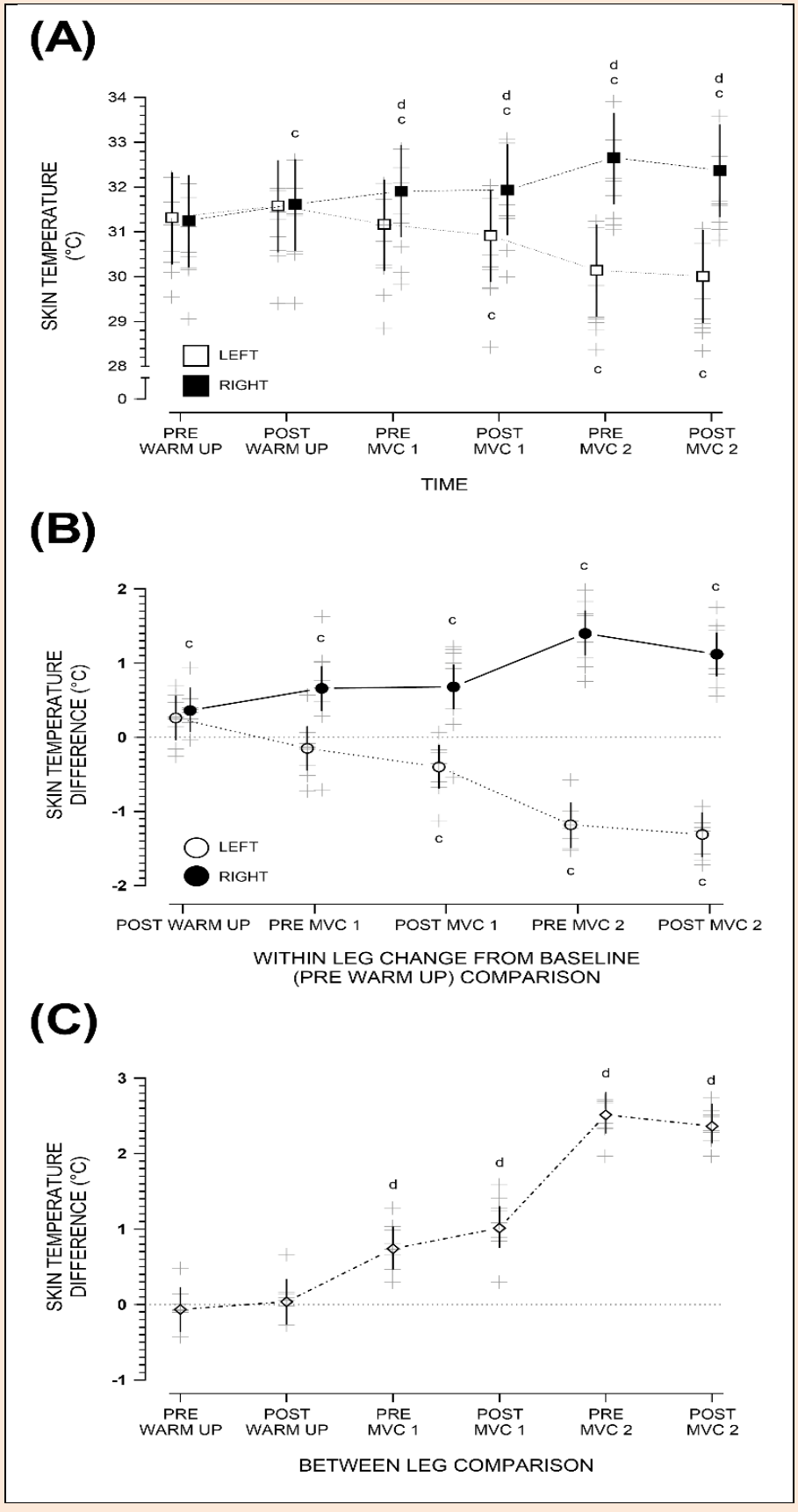

Figure 3. Posterior mean (95% credible interval, CI) anterior RIGHT and LEFT thigh skin temperature during the warm-up, and pre- and post-exercise MVC assessments on the first testing day (A); the posterior mean difference (95% CI) of within-leg temperature change from pre-warm up temperature (B); and the posterior mean difference (95% CI) of between-leg comparisons (C). Individual data are shown in cross marks, [c] statistically different to pre warm-up in the same leg, [d] statistically different between legs at the same time point.

Table 2. Posterior mean (95% credible interval) outcomes for neuromuscular variables pre and immediately post the delayed onset muscle soreness inducing exercise protocol.

Variable	Pre	Post
MVC torque (Nm)	227 [194, 259]	**163 [130, 194]**[a]
Voluntary activation (%)	93.6 [90.1, 96.9]	**87.5 [84.0, 90.8]**[a]
Peak twitch torque (Nm)	72 [63, 81]	**37 [28, 47]**[a]
Rate of torque development ($Nm \cdot ms^{-1}$)	794 [712, 877]	**463 [377, 544]**[a]
Contraction time (ms)	164 [143, 184]	**135 [115, 155]**[a]
Half-relaxation time (ms)	71 [58, 84]	**55 [42, 68]**[a]

Statistical differences are bolded, [a] statistically different to baseline (i.e., before exercise).

Discussion

The major finding of this study was that 24 hr following a single leg DOMS-inducing exercise protocol, infra-red imaging was able to detect an elevation in skin temperature of both the exercised and non-exercised (control) limb. During the DOMS protocol the elevation in skin temperature of the exercised thigh was mirrored by a reduction in skin temperature of the non-exercised thigh. These results support both hypotheses stipulated for the exercised limb. However, our findings do not support our hypotheses of no change in skin temperature for the non-exercised limb.

The magnitude and time course of the changes in skin temperature immediately superficial to the exercised thigh muscle (Figure 2) support recent findings (Silva et al., 2017). Following a plyometric program consisting of 5 sets of 20 repetition squat jumps with two minute rests between sets, designed to induce DOMS, thigh skin temperature was elevated by 0.3 °C after 24 hr but had returned to (or below) baseline levels at 48 hr post-exercise. These alterations in skin temperature were observed in two plyometric groups despite one of the groups receiving 15 min of cold-water immersion immediately after the plyometric session. Larger increases in localised skin temperature (1.1 °C) have been recorded 24 hr following a bicep curl protocol (4 sets, 25 repetitions) (Al-Nakhli et al., 2012). Once again, the skin temperature had returned to baseline following 48 hr. The threefold higher skin temperature change may be the result of the differing anatomy between the upper arm and thigh, with differences in cutaneous and intramuscular fat, as well as non-active muscle groups acting as a heat sink and vasculature enhancing heat transfer away from the thigh (Gonzalez-Alonso et al., 2000).

Unique to this investigation, compared to (Al-Nakhli et al., 2012; Silva et al., 2017), was the measurement of the contralateral un-exercised (control) limb both during exercise and for the proceeding 48 hr. With the control thigh displaying changes identical to the exercised thigh post-exercise (Figure 2) indicating that a potential systemic inflammatory response maybe being identified. Large elevations in pro-inflammatory cytokines are observed immediately following eccentric muscle damage, while circulating levels of C-reactive protein have uniformly been shown to peak 24 hr post-exercise (Pournot et al., 2011). The fever induced with acute inflammation is due to the production of these pro-inflammatory cytokines (MacIntyre et al., 1995). Supporting this time course Silva et al (Silva et al., 2017) identified a similar magnitude of change in forehead skin temperature at 24 hr post- but not 48 hr post-exercise. Alternatively, the increased ambient temperature at the 24 hr time point, in the current study, might also explain the higher skin temperature in both limbs. However, the reduction in skin temperature at 48 hr while ambient temperature remained elevated compared with baseline does not support this explanation.

Increasing muscle contraction resulted in the expected significant increase in the exercising thigh skin temperature (Figure 3). These increases became apparent following the warm-up and had their largest effect following the DOMS-inducing exercise protocol (1.4 °C compared with baseline). The reduction in skin temperature of the control thigh during the exercise protocols mirrored the exercising thigh response (Figure 3A, 3B). This phenomenon has been observed previously in a single participant performing concentric only contractions of the quadriceps at 120 $°\cdot s^{-1}$ for 7.5 min (Hadzic et al., 2019). Redistribution of blood flow towards exercising skeletal muscle may explain the acute changes in skin temperature of both thighs. Following an immediate transient vasodilation of the femoral artery during single leg exercise, blood flow to the non-active contralateral limb is reduced. Increased muscle sympathetic neural activity in combination with the muscle metaboreflex may result in vasoconstriction of the branches of the femoral artery feeding the control thigh reducing blood flow below resting levels (Yoshizawa et al., 2008).

Large reductions in knee extensor MVC torque, VA and twitch properties were observed immediately after the exercise protocol (Table 2). Notably, despite the recovery of VA within 24 hr, changes in MVC torque and some twitch properties remained present 48 hr post-exercise (Table 1). Given the relative vigour of the dynamometer protocol (i.e., 6 x 25 repetitions, CON/ECC angular velocity: 60/120 $°\cdot s^{-1}$), we expected considerable biomechanical consequences would be observed owing to structural contractile damage and altered calcium ion or sodium/potassium ion pump function (Allen et al., 2008). Reductions in peak twitch torque and longer rates of torque development, albeit not statistically, in the presence of a stable VA 24 hr and 48 hr post-exercise, respectively, suggest peripheral muscle damage was evident (Sayers et al., 2003). Elevated muscle soreness at both of these timepoints reinforces this interpretation. It is interesting, however, that despite using a comparable exercise protocol, Pointon et al. (Pointon et al., 2011) report sustained reductions in VA 48 hr post-exercise, indicative of central nervous system contributions to the MVC torque decline. Further perplexing is that this greater neuromuscular perturbation was achieved in a

resistance trained sample (Pointon et al., 2011), as compared with the healthy active group reported here. Irrespective, the varied time-course recovery of our neuromuscular data (i.e., central and peripheral) and perceptual soreness measures is expected (Minett and Duffield, 2014), but should be interpreted with care.

Participants in the current study, with a history of resistance training anecdotally had less neuromuscular impairment and reported less soreness than those who had minimal to no resistance training experience. In order to complete the number of repetitions within the current DOMS-inducing exercise protocol, certain participants required longer rest between sets. Future research should attempt to recruit a more homogeneous group with respect to resistance training experience and/or for the experienced participants employ a more aggressive DOMS protocol (i.e., less rest between sets). Alternatively, a between-group design using a larger cohort of participants, across various training backgrounds, would enable an investigation of the discriminatory capability of infra-red imaging. Such an investigation would allow the comparison of skin temperature between those that exhibited DOMS, and those that did not, following an exercise protocol.

Conclusion

In conclusion, the results of this study indicate that infra-red imaging was able to differentiate changes in skin temperature during exercise, between the exercising and non-exercising thighs, that coincided with muscle activity. However, while infra-red imaging was able to detect elevations, as expected, in skin temperature of the exercising thigh, at 24 hr after the DOMS inducing exercise protocol, these elevations were surprisingly also recorded in the non-exercising thigh. The increase in skin temperature of both thighs is possibly reflective of a systemic inflammatory response. Further studies are required to elucidate the mechanism of the observed increase in skin temperature.

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Key points

- Infrared imaging detected elevations in skin temperature 24 h following a single leg DOMS inducing exercise protocol.
- Skin temperature elevations 24 h post-exercise were detected in both the exercised and non-exercised (control) thighs.
- The exercised thigh exhibited elevations in skin temperature during the exercise protocol that were mirrored by reductions in skin temperature in the control thigh.

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