Journal of Thermal Biology 130 (2025) 104156

Contents lists available at ScienceDirect

Journal of Thermal Biology

journal homepage: www.elsevier.com/locate/jtherbio

Passive thigh heating improves isokinetic but not isotonic muscle function

Desmond Denny[a], Daniel C. Low[a,b], Oliver R. Gibson[a,b,*]

[a] Department of Sport, Health and Exercise Sciences, College of Health, Medicine and Life Sciences, Brunel University of London, Uxbridge, UK
[b] Centre for Physical Activity in Health and Disease (CPAHD), Brunel University of London, Uxbridge, UK

ARTICLE INFO

Keywords:
Muscle strength
Force development
Torque
Hyperthermia
Passive heating
Thermal therapy

ABSTRACT

Purpose: Optimal skeletal muscle function occurs when tissue temperature is elevated above resting. This study examined muscle torque production and maximal velocity responses to passive thigh heating on two occasions to determine the efficacy and reliability of the intervention.
Methods: Twenty active, young participants (10 female) completed two identical visits whereby one thigh was wrapped in a water perfused garment circulating 50 °C water for 90 min; with the contralateral limb remaining unheated. Four maximal isokinetic repetitions were conducted at three speeds (slow, 60°/s; moderate, 180°/s; fast, 300°/s) followed by an isotonic set (25% MVIC) to assess muscle function on both limbs at baseline and every 30 min for 90 min. Muscle temperature (*vastus lateralis*) was assessed every 30 min.
Results: Heating increased muscle temperature from baseline (32.2 ± 1.1 °C) to 30 min (36.8 ± 0.7 °C) with further 0.4 ± 1.3 °C increases in the following 30 min periods ($p < .05$). Heating increased peak torque during moderate (+10 ± 12 N m) and fast (+10 ± 11 N m) contractions from 30 min onwards relative to the unchanged control leg ($p < .05$). Peak torque during slow isokinetic and isotonic contractions were unchanged. Rate of force production and early force production increased in from baseline in the heated leg during the slow contractions by 14 % and 15 % respectively, whilst the control leg was unchanged throughout. Isokinetic and isotonic force muscle function was found to have excellent reliability across all contractile speeds (ICC>0.9)
Discussion: Passive heating of skeletal muscle improves peak torque production during moderate and fast isokinetic contractions and increases early force production in slow isokinetic contractions.

1. Introduction

Optimal muscle function for physical activity occurs at temperatures above the physiological resting range i.e., 32–35 °C (Bishop, 2003). Muscle temperature is usually increased prior to exercise requiring high force or high velocity contractions through an active (exercise) warm-up, which can increase muscle temperature by ≥ 3 °C (Marshall et al., 2015). Passive heating of skeletal muscle to increase muscle temperature prior to undertaking high force or high velocity contractions is an emerging field of research and has been proposed to be of benefit as a supplement to an active warm up, or even as a replacement for those who cannot partake in an active warm up before they engage in physical activity (McGorm et al., 2018), e.g., the elderly and those undergoing physical therapy. Passive heating induces localised hyperthermia, i.e., an elevated temperature of target tissue e.g., skeletal muscle, by up to 6.5 °C (Mitchell et al., 2008; Koch et al., 2021; Watanabe et al., 2024) with this likely an optimal temperature elevation given temperatures ≥42 °C potentiate protein degradation and declines in contractile function (Baracos et al., 1984; Ranatunga, 1984; Essig et al., 1985). Passive heating interventions can be implemented by a variety of means including hot water baths (Rodrigues et al., 2020b; Jackman et al., 2023), water perfused garments (Kim et al., 2020b; Gibson et al., 2023), heated pads (Goto et al., 2011), microwave diathermy (Draper et al., 1999; Kim et al., 2020a) and environmental chambers (Ihsan et al., 2020; Sweet et al., 2024). Whilst all methods share the same primary outcome i.e., increased temperature of the skeletal muscle associated with impending contraction; whole body heating modalities often also increase core temperature. This systemic (whole body) rather than local hyperthermia decreases central drive to the muscle impairing force production (Thomas et al., 2006). To avoid this, local heating increases muscle temperature whilst maintaining core temperature at normothermic levels (Kim et al., 2020b; Gibson et al., 2023), with data demonstrating that this local response is ergogenic (Rodrigues et al., 2021).

Initial research investigating the effect of passive heat on muscle function primarily focused on cycle ergometry (Bergh and Ekblom, 1979; Sargeant, 1987) or field testing (Oksa et al., 1996) with later work

* Corresponding author. College of Health, Medicine and Life Sciences Brunel University of London, Kingston Lane, Uxbridge, UB8 3PH, UK.
E-mail address: oliver.gibson@brunel.ac.uk (O.R. Gibson).

https://doi.org/10.1016/j.jtherbio.2025.104156
Received 29 January 2025; Received in revised form 7 May 2025; Accepted 25 May 2025
Available online 3 June 2025

List of abbreviations

ANOVA	Analysis of variance
Ca^{2+}	Calcium ion
CONT	Control condition
DBP	Diastolic blood pressure
EFP	Early force production
EVP	Early velocity production
HEAT	Heated condition
HR	Heart rate
ICC	Intraclass correlation coefficient
MAP	Mean arterial pressure
MDC_{95}	Minimal detectable change
MVIC	Maximal voluntary isometric contraction
RFD_{50}	Rate of force development at 50 ms
SBP	Systolic blood pressure
SEM	Standard error of measurement
SERCA	Sarcoplasmic reticulum Ca ATPase
T_{mu}	Muscle temperature
T_{skin}	Skin temperature
T_{tymp}	Tympanic temperature

investigating team sport simulations (West et al., 2016). Current research in this domain has primarily focused on isometric contractions which have demonstrated increased rate of force production and increased peak force production following hyperthermia (Rodrigues et al., 2021; Mornas et al., 2022; Chang et al., 2023). Whilst isometric contractions provide a controlled state to observe modifications in muscle function, they do not reflect the demands of dynamic daily living tasks, such as standing from a chair or locomotion, or sport-specific physical activities. Accordingly, insights into the potential benefits arising from passive heating interventions on dynamic (isokinetic/isotonic) contractions is required. Dynamic muscle function testing is often conducted using dynamometry and this technique is considered the gold standard for knee extensor muscle function assessment, due to its high accuracy and reliability when assessing peak isometric (de Araujo Ribeiro Alvares et al., 2015), isokinetic (Feiring et al., 1990) and isotonic force production (Timm et al., 1992). Additionally, dynamometry readily facilitates the assessment of muscle function across a variety of contractile speeds, often between 30 and 300°/s (Ivy et al., 1981; Molczyk et al., 1991; Grbic et al., 2017), which may provide translational and mechanistic insight (Taylor et al., 1991; Tsiros et al., 2011). Finally, early rate of force production in lower limb muscles, i.e., force within 0–300 ms of contraction onset, is associated with effective sporting performance (Hernández-Davó and Sabido, 2014) and quality of life in older adults (Thompson et al., 2014), with changes quantifiable via dynamometry. Despite emerging data describing the ergogenic benefit of passive heating during the early stage of evoked isometric contractions (Rodrigues et al., 2021), at present there is a paucity of data examining the efficacy of passive heating to increase peak force production during dynamic contractions, with only a few papers investigating the topic (Cheung and Sleivert, 2004; Skurvydas et al., 2008; Ramanauskiene et al., 2008). Although the physiological benefits of passive heating are being investigated, the perceptual responses have not yet been adequately studied. It is essential to thoroughly understand how participants subjectively experience passive heating to develop an intervention that is not only tolerable but also perceived as beneficial. Accordingly, there is a need to investigate the influence of local passive heating on dynamic contractions which represent real world contexts.

The reliability of physiological and functional outcomes during passive heating have seldom been reported. In the absence of this understanding, it is challenging to fully understand the true observed effect and minimal change required to be meaningful. In general, the reliability of knee extension exercise during dynamometry is considered excellent [intraclass correlations (ICC) > 0.9) (Sáenz et al., 2010)]. Without assessing the reliability of this protocol only assumptions can be made regarding natural variation and error associated with the experimental design increasing the chance for type I errors to occur (Webb, 1992). Despite this, to the best of the authors' knowledge there is yet to be a comprehensive assessment of the inter-day reliability of knee extension exercise during prolonged passive heating interventions relative to an unheated time control.

The first aim of this experiment was to quantify the intra and inter-day reliability of muscle function and local (to the thigh) and systemic (whole body) physiological responses before and during 90 min passive thigh heating or control in a cohort of healthy young adults (Part 1). It was hypothesised that i) peak isokinetic torque, peak isotonic velocity, early force production (EFP) and rate of force development (RFD) measures taken during the heating protocol would display excellent inter and intraday reliability, ii) physiological measures would also display excellent inter and intraday reliability. The second aim of this study was to observe the interaction between skeletal muscle hyperthermia and torque production with a view to understanding whether passive heating can enhance peak force production, utilising the established reliability data to explain observations (Part 2). In relation to this aim, it was hypothesised that muscle hyperthermia would increase peak isokinetic torque production including EFP and RFD across all contractile speeds, and that peak isotonic contractile velocity would be increased.

2. Method

2.1. Participant characteristics

Twenty active participants (ten female, age 23 ± 2 y, height 1.72 ± 0.08 m, mass 68.5 ± 73.2 kg, BMI 23.1 ± 3.3 kg/m^2, body fat 17 ± 4 %, peak isometric force, heated limb 238 ± 70 N, control limb 201 ± 65 N, all partaking in >60 min week of physical activity) free of known illness and disease completed the study. All participants were non-smokers, with no history of heat intolerance or neuromuscular disorders and provided written informed consent prior to taking part. To examine the reliability of the intervention, an estimated sample size of 20 participants was calculated *a priori* using a formula provided from Walter et al. (1998) provided in Borg et al. (2022), whereby the expected intraclass coefficient for isokinetic dynamometry was predicted to be ≥ 0.9 (Maffiuletti et al., 2007); with a precision of 0.1 and a confidence level of 95 % with two retest occasions. Sample size estimation associated with determining the ergogenic potential of the heating intervention identified that <20 participants were required. As this was fewer than the number of participants required for the reliability analysis, twenty participants were recruited. Female participants were requested to schedule both visits within the same menstrual cycle phase. The study was approved by the Brunel University of London Research Ethics Committee and was carried out in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants prior to commencement of the study.

2.2. Experimental design

Participants attended the laboratory to undertake two identical visits on two separate days at either at 9:00 or 13:00. Visits were separated by 7 ± 2 days and time matched for each participant. The room temperature was measured to be 19 ± 2 °C across all testing days. Participants abstained from heavy exercise (e.g. resistance or interval training, prolonged endurance activity or competitive sport), caffeinated drinks and supplements, and alcohol for 24 h prior to the experimental visits. The first visit began with an assessment of anthropometric characteristics. Unshod standing stature was recorded using a stadiometer (SECA model 213, Hamburg, Germany), with mass was assessed using electronic scales (SECA model 875, Hamburg, Germany). Body fat percentage was determined in accordance with the Durnin and Womersley (1974) four-site skinfold method. Following anthropometry and body composition assessments, physiological and perceptual measures were assessed first, followed by muscle function. These measures were taken at baseline, then +30, +60, +90 min thereafter on both limbs. Following instrumentation, the right leg (60 % of participants' dominant limb) was selected to have the upper thigh heated for 90 min (HEAT) whist the contralateral limb served as a control (CONT). The participants wore leggings with the experimental thigh (HEAT) wrapped in a custom garment consisting of silicon tubes enclosed in cotton material that circulated water at an outlet temperature of 50 °C and a survival blanket for a period of 90 min. Fig. 1 displays the custom heated garment uncovered by survival blanket. The garment remained on the thigh for the entire testing protocol, including during muscle function assessment, whilst the contralateral control thigh (CONT) was left uncovered. The same limbs served as HEAT and CONT legs on both visits. The participants remained seated on the dynamometer throughout the testing protocol. Whilst not engaged in dynamometry exercise the participants had their feet resting on a chair with their knees bent at a ~90° angle. All contractions were conducted through a 75°–175° range of motion. See Fig. 1 for a schematic of the full testing protocol conducted during each visit.

2.3. Physiological and perceptual measures

A tympanic membrane temperature device (Brawn Thermoscan 7, Bussigny, Switzerland) was set to the appropriate age setting and then fully inserted into the right ear canal whereby tympanic temperature (T_{tymp}) was recorded as a surrogate for core temperature. Heart rate (HR) and systolic (SBP) and diastolic blood pressure (DBP) and mean arterial pressure (MAP) were measured via an automated sphygmomanometer placed over the left brachial artery (Carescape V100 VitalSigns Monitor, Bolton). Muscle temperature (T_{mu}) was recorded using a muscle temperature probe (RS 103-433 K-type thermocouple, England). The probe was inserted, without local anaesthesia, ~30 mm below the skin surface at a 45° to the horizontal into the *vastus lateralis* via an 18-gauge hypodermic needle (Microlance 3, Ireland). Muscle temperature was manually recorded following temperature stabilisation (typically ~5 s) with the probe and guide needle removed thereafter. Wireless

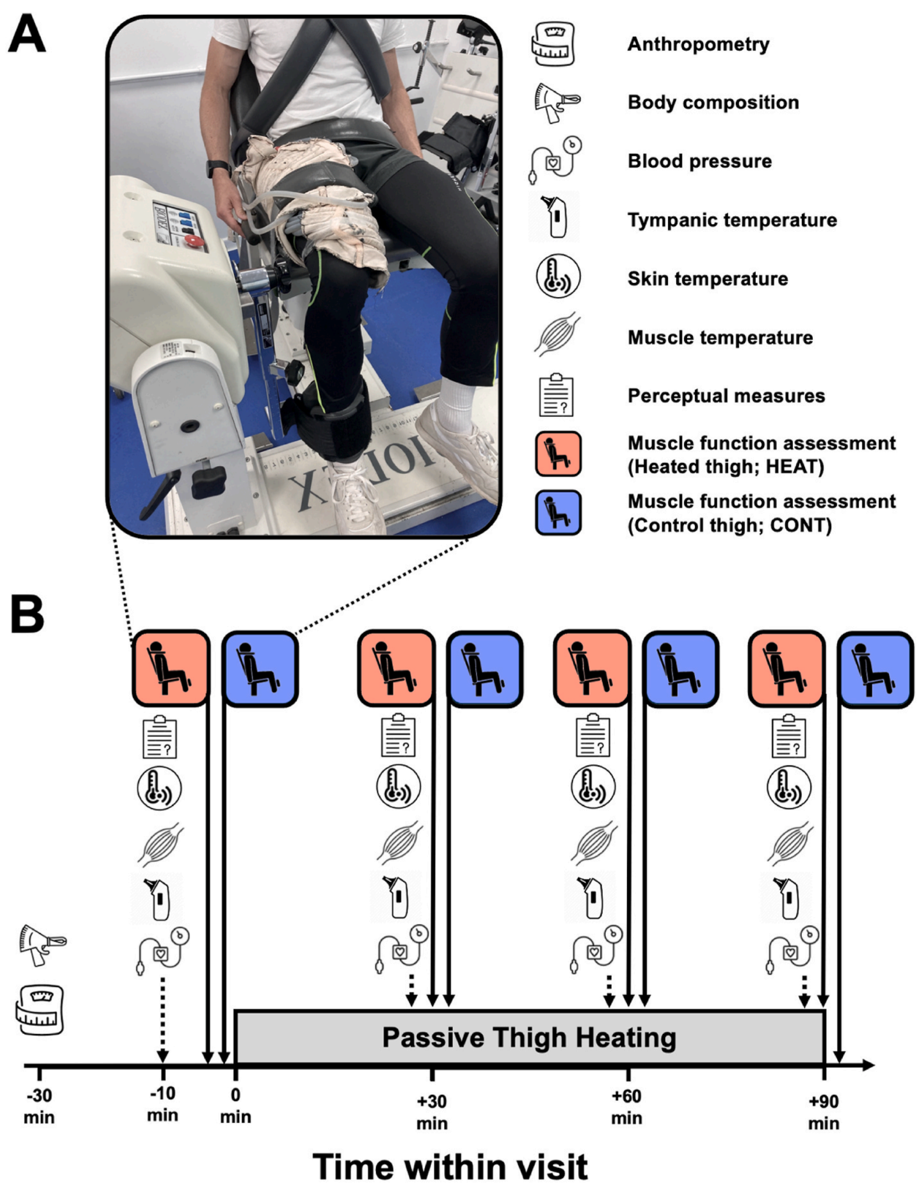

Fig. 1. Image of the custom-made water perfused heated garment as affixed on the thigh without the covering of the survival blanket (A). Sequence of the experimental protocols (B).

iButton (DS1922L Thermochron Data Logger, UK) sensors were placed on the muscle belly of the *vastus lateralis* and used to measure thigh skin temperature (T_{skin}) at 1-min intervals. Participants responded to a global rate of change scale (+7 A very great deal better, +4 Moderately better, 0 About the same, −4 Moderately worse, −7 A very great deal worse) (Bobos et al., 2020), and thermal sensation scale (0.0 Unbearable Cold, 2.0 Cold, 4.0 Neutral (Comfortable), 6.0 Hot, 8.0 Unbearably Hot) (Young et al., 1987) prior to assessment of muscle function. A rate of perceived exertion scale (6 No exertion, 7 Very, very light, 13 Somewhat hard, 19 Very, very hard, 20 Maximal exertion) (Borg, 1990) was shown and answered by participants after every set of knee extension at 60°/s.

2.4. Muscle function

Following the assessment of physiological measures, knee extensor function was assessed using a dynamometer (Biodex Medical Systems, Shirley, NY, USA). A warmup of 10 submaximal knee extensions (five at 50 % maximum effort, three at 75 % maximum effort, two at 90 of maximum effort) was conducted on each leg at a self-selected intensity and an assessment of their maximal voluntary isometric contraction force (MVIC) made on both limbs. At baseline (0 min), and +30, +60, +90 min thereafter participants performed four repetitions of maximal isokinetic knee extension at 60°/s, 180°/s, and 300°/s, separated by 60 s passive rest, then performed four isotonic contractions against 25 % of their MVIC force. Testing was conducted in accordance with previous work investigating isokinetic (Blazquez et al., 2013) and isotonic muscle function (Cheng and Rice, 2005). At all timepoints the HEAT limb was assessed in full first, followed by CONT, therefore CONT testing occurred ~5 min following HEAT. The singular highest recorded torque value of each set were used independently for torque analysis, unless stated, across all contraction types at every timepoint. Rate of force development at 50 ms (RFD_{50}) was calculated as the first positive torque data point subtracted from the torque value at 50 ms after the first recorded value which was then divided by the time elapsed in seconds (Maffiuletti

Table 1
The inter-day coefficient of variation (CV), minimal detectable change (MDC_{95}), statistical reliability (ICC) analysis, and intraday MDC_{95} of peak force, EFP and RFD_{50} within isokinetic and isotonic contractions and physiological and perceptual responses to 90 min of passive thigh heating (n = 20).

	CV%					SEM	Interday ICC				MDC_{95}
	0 min	30 min	60 min	90 min	All timepoints	Inter-day	Estimation	Upper 95 % confidence	Lower 95 % Confidence	Cronbach's α	Intraday
60/S HEAT (N.m)	9.6	7.7	8.6	8.0	8.5	3	0.93	0.95	0.88	0.96	9
60/S CONT (N.m)	8.5	6.7	6.0	7.9	7.3		0.94	0.96	0.90	0.97	
180/S HEAT (N.m)	11.0	5.9	4.8	5.6	6.9	2	0.95	0.97	0.93	0.98	6
180/S CONT (N.m)	7.5	6.9	6.1	5.2	6.4		0.94	0.96	0.90	0.97	
300/S HEAT (N.m)	8.5	6.1	4.7	5.0	6.1	3	0.95	0.97	0.92	0.97	7
300/S CONT (N.m)	9.8	7.3	8.1	6.4	7.9		0.91	0.95	0.85	0.96	
25 % MVIC HEAT (°/s)	3.9	3.9	4.5	4.8	4.3	6	0.85	0.87	0.75	0.98	17
25 % MVIC CONT (°/s)	3.9	3.1	3.7	5.5	4.0		0.82	0.85	0.70	0.97	
RFD 60/S HEAT (N.m. s^{-1})	25.0	10.3	11.4	11.7	14.6	42	0.84	0.90	0.74	0.92	99
RFD 60/S CONT (N.m. s^{-1})	10.7	15.2	8.3	10.1	11.1		0.82	0.90	0.76	0.91	72
RFD 180/S HEAT (N.m.s^{-1})	32.4	18.7	13.5	15.3	20.0	79	0.84	0.91	0.69	0.93	109
RFD 180/S CONT (N.m.s^{-1})	24.8	20.2	21.9	18.1	21.3		0.81	0.89	0.64	0.91	102
RFD 300/S HEAT (N.m.s^{-1})	48.9	23.3	27.4	30.0	32.4	34	0.83	0.95	0.83	0.92	97
RFD 300/S CONT (N.m.s^{-1})	35.4	26.9	32.7	33.8	32.3		0.89	0.94	0.79	0.95	68
RFD 25 % MVIC HEAT (N.m.s^{-1})	32.5	40.1	29.3	34.7	34.1	114	0.39	0.56	0.19	0.56	67
RFD 25 % MVIC CONT (N.m.s^{-1})	42.0	35.7	48.6	37.4	41.0		0.04	0.25	0.0	0.08	83
EFP 60/S HEAT (N.m)	13.3	8.8	6.5	8.8	9.3	5	0.94	0.96	0.90	0.97	8
EFP 60/S CONT (N.m)	14.7	13.0	7.9	7.6	10.8		0.89	0.93	0.83	0.94	9
EFP 180/S HEAT (N.m)	10.7	5.3	5.5	5.6	6.8	2	0.96	0.97	0.93	0.98	5
EFP 180/S CONT (N.m)	7.0	6.0	4.4	5.3	5.7		0.94	0.97	0.93	0.98	4
EFP 300/S HEAT (N.m)	8.6	15.1	5.9	9.1	9.7	3	0.90	0.93	0.85	0.95	5
EFP 300/S CONT (N.m)	9.8	8.4	10.0	9.9	9.5		0.88	0.92	0.82	0.94	5
EVP 25 % MVIC HEAT (°/s)	8.4	6.7	9.9	8.4	8.4	13	0.85	0.90	0.78	0.92	17
EVP 25 % MVIC CONT (°/s)	10.2	13.1	8.9	5.7	9.5		0.82	0.88	0.72	0.91	18
T_{mu} HEAT	5.1	2.5	2.1	1.3	2.8	1	0.74	0.86	0.55	0.85	3
T_{mu} CONT (°C)	2.6	2.7	3.1	3.5	3.0		0.49	0.70	0.19	0.65	
T_{skin} HEAT (°C)	1.8	1.1	1.6	1.8	1.6	1	0.98	0.99	0.96	0.99	3
T_{skin} CONT (°C)	2.3	2.6	2.5	2.5	2.3		0.79	0.86	0.63	0.88	
T_{tymp} (°C)	0.7	0.4	0.6	0.5	0.6	0.2	0.59	0.73	0.42	0.93	1
SBP (mmHg)	6.1	5.8	3.7	6.1	5.4	9	0.57	0.75	0.40	0.92	25
DBP (mmHg)	8.3	5.8	6.8	5.5	6.6	9	0.62	0.79	0.45	0.94	25
MAP (mmHg)	6.8	4.9	4.1	5.2	5.2	5	0.64	0.80	0.48	0.94	14
HR (b.min^{-1})	10.0	8.8	9.4	8.1	9.1	8	0.46	0.66	0.29	0.88	22
Thermal Sensation	16.0	7.4	7.0	10.2	10.1	1	0.52	0.66	0.34	0.70	3
RPE HEAT	7.2	8.6	6.1	7.5	7.4	1	0.51	0.66	0.33	0.68	3
RPE CONT	6.3	6.9	6.9	6.3	6.6		0.34	0.52	0.13	0.51	

et al., 2016). RFD_{50} was calculated for repetitions at 60°/s (RFD_{slow}), 180°/s (RFD_{mod}), 300°/s (RFD_{fast}) and for the isotonic contractions at 25 % MVIC force ($RFD_{isotonic}$) Early force production (EFP) was calculated as peak torque produced at 0.18 s (Amaral et al., 2014) during the 4 repetitions at each velocity (i.e. at 60°/s (EFP_{60}), 180°/s (EFP_{180}), 300°/s (EFP_{300}) and 25 % MVIC force (EVP_{25})). The Biodex system 4 software was used to collect data at 100 Hz (Biodex Medical Systems, Shirley, NY, USA). Torque, position, and velocity data was collected within software every 10 ms then exported without filtering and imported to Microsoft Excel for analysis.

2.5. Statistical analysis

To confirm reliability of the protocol-intervention interaction, single measures ICC was chosen as the most appropriate measure of repeatability for the muscle function tests (Koo and Li, 2016), ICC estimates were calculated using absolute-agreement two-way mixed effects model (ICC3,1) and was used to identify the intra-day reliability of peak torque, EFP and RFD_{50} produced for the heated and control leg during isokinetic contractions at 60°/s, 180°/s, 300°/s, and during isotonic contractions at 25 % of MVIC force across four timepoints (0, +30, +60, +90 min). The inter-day reliability was also calculated between all data collected on the CONT limb as no change was expected over time. In addition, Cronbach's Alpha (Cα) was used to calculate statistical reliability for the systemic physiological responses and the psychological test answers, this was more appropriate due to the smaller number of datapoints and provided an averaged measures consistency result, for full transparency both statistical analyses for all measures are included in Table 1. Single measures ICC and Cronbach's Alpha results were categorised as having excellent reliability if scores were >0.90, good reliability if scores were >0.75, moderate reliability >0.50 and poor reliability for any values < 0.50 (Koo and Li, 2016). Coefficient of variance (CV) was calculated as the ratio between the standard deviation and the mean of each participant between visit 1 and visit 2 for each velocity, and each timepoint, independently. The Standard Error of Measurement (SEM) was used to assess response stability via the estimation of the standard error in a set of repeated scores. SEM was calculated by dividing the standard deviation of the sample by the square root of the sample size minus the ICC in accordance with prior research (Weir, 2005). Intra-day SEM was calculated comparing peak baseline to peak 30 min in the control limb. Minimum detectable change (MDC_{95}) is a statistical estimation of the smallest quantifiable change that translates to a noticeable change in real world performance and was calculated in line with prior work (Dontje et al., 2018). To assess responses to the thigh heating intervention and control, data were analysed for normality of distribution using the Shapiro-Wilk test. A three-way repeated-measures Analysis of Variance (ANOVA) was used to determine main effect differences across timepoints (0, +30, +60, +90 min), between conditions (HEAT and CONT) and between visits (visit 1, visit 2) for muscle function T_{mu}, T_{skin} and RPE. Two-way ANOVA was used to determine main effect differences across timepoints (0, +30, +60, +90 min), and between visits (visit 1, visit 2) for heart rate, blood pressure, thermal sensation and T_{tymp}. Bonferroni post-hoc adjusted pairwise comparisons were used where significant main effects occurred to identify interaction effects between individual timepoints between conditions and visits. All data were analysed using SPSS Statistical Software (Version 25, SPSS, Chicago, IL). Statistical significance was set at $p < .05$, data are reported as mean ± SD unless otherwise stated. Global rate of change scales data were manually counted and reported as frequency of responses.

3. Results

3.1. Part 1: confirmation of reliability

3.1.1. Inter and intraday reliability of physiological and perceptual measures during passive thigh heating

The inter-day CV, ICC and MDC_{95} and intraday MDC_{95} was calculated for all physiological and perceptual measures (Table 1). When averaged across all timepoints all measures displayed low inter-day variability i.e., CV ≤ 10 %. Skin temperature across timepoints in HEAT demonstrated excellent intra-day reliability (Cronbach's α > .90) highlighting that the intervention delivered a consistent stimulus, with CONT T_{sk} demonstrating good reliability (Cronbach's α > .75). Blood pressure and T_{tymp} also scored excellent reliability using the Cronbach's α criteria (>0.9). The T_{mu} in HEAT, demonstrated good reliability (Cronbach's α, >0.75). The T_{mu} in CONT, thermal sensation score and RPE scored moderate reliability (Cronbach's α, >0.05).

3.1.2. Inter and intraday reliability of lower limb force production during passive thigh heating

The inter-day CV, ICC and MDC_{95} and intraday MDC_{95} was calculated for peak torque production, RFD_{50} and EFP at 60°/s, 180°/s and 300°/s contraction speeds, as well as for peak isotonic velocity and EVP at 25 % MVIC force presented in Table 1. Inter day ICC was >0.9 for all heated isokinetic peak torque production and >0.8 for peak isotonic velocity, excellent CV values were displayed in all peak isokinetic torque and isotonic velocity values as well. Inter day ICC was >0.9 for all heated EFP and >0.8 for EVP. Excellent CV values were displayed within heated and control EFP_{180} and $EFP_{25\ \%}$. Good CV values were observed in EFP_{60} and EFP_{300}. All isokinetic RFD_{50} displayed good ICC >0.8 scores, whilst the $RFD_{isotonic}$ displayed poor reliability (ICC <0.5). Poor CV values were observed for all RFD_{50} values.

3.2. Part 2: responses to passive thigh heating

3.2.1. Local temperature responses to passive thigh heating

Muscle temperature differed when the main effect of Time ($F_{(3,27)}$ = 79.5, p = <0.001, $\eta p^2 = 0.90$), Condition ($F_{(1,9)}$ = 44.5, p = <0.001, ηp^2 = 0.83), Visit*Time ($F_{(3,27)}$ = 5.3, p = .005, $\eta p^2 = 0.37$), Condition *Time ($F_{(3,27)}$ = 51.2, p = <0.001, $\eta p^2 = 0.85$) was investigated. The T_{mu}

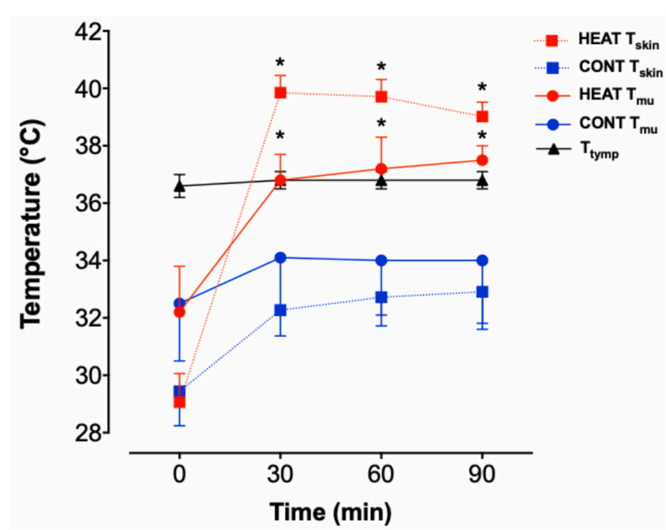

Fig. 2. Mean ± SD Change in muscle temperature (T_{mu}, circles), thigh skin temperature (T_{skin}, squares) and tympanic temperature (T_{tymp}, triangles) during the passive thigh heating protocol (T_{tymp} and T_{skin} n = 20, T_{mu} = 10). * *denotes significant difference between HEAT (red) and CONT (blue) at corresponding timepoint (p < .05).*

in HEAT increased from baseline by 4.6 ± 1.2 °C at 30 min, 5.0 ± 1.3 °C by 60 min and 5.3 ± 1.2 °C by 90 min, see Fig. 2. The T_{mu} in CONT increased from baseline by 1.5 ± 1.4 °C at 30 min and maintained this temperature increase throughout testing. Skin temperature (Fig. 2) differed when observing main effects within Condition ($F_{(1,7)} = 300.4$, p = <0.001, $\eta p^2 = 0.98$), Time ($F_{(3,21)} = 313.0$, p = <0.001, $\eta p^2 = 0.98$), Condition*Time ($F_{(3,21)} = 181.4$, p = <0.001, $\eta p^2 = 0.96$). Post hoc testing revealed that T_{skin} increased in HEAT by 11 ± 1 °C at 30 min which was sustained throughout the 90 min of heating. The CONT T_{skin} increased from baseline by 3 ± 1 °C and maintained this temperature increase throughout testing.

3.2.2. Systemic physiological responses to passive thigh heating

Heart rate differed when the main effects of Time ($F_{(3,57)} = 7.7$, p = .003, $\eta p^2 = 0.29$) were tested. Post hoc testing revealed that HR increased by 7 ± 10 b min^{-1} after baseline and remained at this until 60 min, no significant difference was observed at 90 min. Systolic blood pressure differed only when the main effects of Time ($F_{(3,57)} = 6.7$, p = <0.001, $\eta p^2 = 0.26$) was examined. SBP reduced by 9 ± 11 mmHg from baseline at 30 min, 7 ± 10 mmHg at 60 min and 5 ± 11 mmHg at 90 min. Diastolic blood pressure (DBP) differed when the main effects of Time ($F_{(3,57)} = 5.1$, p = .003, $\eta p^2 = 0.21$) and Visit ($F_{(1,19)} = 4.7$, p = .043, $\eta p^2 = 0.20$). There was a 3 ± 6 mmHg reduction in DBP in visit 2 and a 3 ± 6 mmHg reduction from baseline after 30 min that persisted until the end of testing. Mean arterial pressure (MAP) differed when the main effects of Time ($F_{(3,57)} = 8.7$, p = <0.001, $\eta p^2 = 0.32$) were tested. MAP reduced by 5 ± 6 mmHg after baseline and remained at this value thereafter. Tympanic temperature differed upon observing the main effect of Time only ($F_{(3,57)} = 10.8$, p = <0.001, $\eta p^2 = 1.0$) increasing by 0.2 ± 0.3 °C at 30 min and maintained thereafter. No difference was observed between visits.

3.2.3. Torque production following upper thigh muscle hyperthermia

Peak force production at 60°/s only differed where the main effects of Condition were observed ($F_{(1,19)} = 8.1$, p = .010, $\eta p^2 = 0.25$). Peak force production at 180°/s differed when the main effects of Condition ($F_{(3,57)} = 9.9$, p = .005, $\eta p^2 = 0.34$), and Condition*Time ($F_{(3,57)} = 4.5$, p = .012, $\eta p^2 = 0.19$) were examined. Post hoc comparisons are in Table 3 and Fig. 3, whereby heating improved torque production by +10 ± 16 N m vs control from 30 min onwards ($p < .05$). The MDC_{95} for this measure was 6 N m, 65 % of the cohort could there be considered meaningfully changed beyond chance. Peak force production at 300°/s differed when the main effects of Visit ($F_{(1,19)} = 7.6$, p = .013, $\eta p^2 = 0.29$), Condition ($F_{(3,57)} = 12.0$, p = .003, $\eta p^2 = 0.39$), Visit*Time ($F_{(3,57)} = 2.9$, p = .041, $\eta p^2 = 0.13$) and Time* Condition ($F_{(3,57)} = 7.1$, p = <0.001, $\eta p^2 = 0.27$) were examined. Full post hoc comparisons of all interactions of force production at 300°/s are located in Table 3 and revealed a +4 ± 6 N m increase in visit 2 vs visit 1 ($p < .05$) and an increase in force production during 300°/s contractions by +10 ± 11 N m in the heated condition vs control from 30 min onwards ($p < .05$). The MDC_{95} for this measure was 7 N m, 75 % of the cohort could therefore be considered as meaningfully increased beyond chance. Peak velocity at 25 % of MVIC force differed when the main effect of Visit ($F_{(1,19)} = 4.7$, p = .042, $\eta p^2 = 0.20$) was examined. Post hoc testing, located in Table 3 revealed peak velocity at 25 % of MVIC force was 8°/s greater in visit 1 vs visit 2 ($p < .05$) (see Fig. 4).

3.2.4. Rate of force development and early stage force production following upper thigh muscle hyperthermia

RFD_{slow} differed when the main effects of Condition ($F_{(1,19)} = 5.7$, p = .027, $\eta p^2 = 0.23$), Time ($F_{(3,57)} = 4.7$, p = .005, $\eta p^2 = 0.20$), Condition*Visit ($F_{(1,19)} = 8.6$, p = .009, $\eta p^2 = 0.31$), Condition*Time ($F_{(3,57)} = 7.4$, p = <0.001, $\eta p^2 = 0.28$) and Visit*Time ($F_{(3,57)} = 8.4$, p = <0.001, $\eta p^2 = 0.31$). Post hoc comparisons are in Table 3 whereby only HEAT showed improved RFD_{50} from baseline by +122 ± 133 N.m.s^{-1} at 30 min, +154 ± 168 N.m.s^{-1} at 60 min and +155 ± 187 N.m.s^{-1}. No significant difference was observed between HEAT and CONT at baseline, HEAT was improved compared to CONT after 30 min by +143 ± 226 N.m.s^{-1}, 60 min by +151 ± 188 N.m.s^{-1} and 90 min + 156 ± 313 N.m.s^{-1}. RFD_{mod} differed when the main effects of Condition ($F_{(1,19)} = 7.4$, p = .014, $\eta p^2 = 0.28$), Visit ($F_{(1,19)} = 14.7$, p = .001, $\eta p^2 = 0.44$), Time ($F_{(3,57)} = 3.7$, p = .035, $\eta p^2 = 0.16$), Condition*Time ($F_{(3,57)} = 3.2$, p = .046, $\eta p^2 = 0.14$) and Visit*Time ($F_{(3,57)} = 4.1$, p = .022, $\eta p^2 = 0.18$). Post hoc comparisons are in Table 3 whereby only HEAT showed improved RFD_{50} from baseline by +142 ± 259 N.m.s^{-1} at 30 min, +158 ± 256 N.m.s^{-1} at 60 min and +138 ± 224 N.m.s^{-1}. No significant difference was observed between HEAT and CONT at baseline or 30 min, HEAT was improved compared to CONT after 60 min by +133 ± 174 N.m.s^{-1} and 90 min + 129 ± 192 N.m.s^{-1}. Visit 2 had an increased RFD_{50} at baseline +241 ± 224 N.m.s-1, 30 min + 142 ± 197 N.m.s-1and at 90 min + 120 ± 233 N.m.s^{-1}. RFD_{fast} differed when the main effects of Visit ($F_{(1,19)} = 13.6$, p = .002, $\eta p^2 = 0.42$), no other main or interaction effects were observed. Post hoc testing revealed that visit 2 displayed higher RFD_{50} results, visit 1 averaged 533 ± 416 N.m.s^{-1} whilst visit 2 averaged 634 ± 443 N.m.s^{-1}. There was no significant main or interaction effects when observing $RFD_{isotonic}$.

Early force production at 0.18 s (60°/s) (EFP_{60}) differed when the main effects of Time ($F(_{(3,57)} = 16.9$, p = <0.001, $\eta p^2 = 0.47$), Visit*Time ($F_{(3,57)} = 5.6$, p = .002, $\eta p^2 = 0.23$) and Condition*Time ($F_{(3,57)} = 4.0$, p = .012, $\eta p^2 = 0.23$) were examined. EFP_{60} did not differ over Time, or for the Visit* Condition interaction. Post hoc comparisons are in Table 3 and Fig. 3, whereby heating improved EFP_{60} by +12 ± 22 N m vs control from 60 min, and +18 ± 15 N m within HEAT from baseline after 90 min. EFP_{60} was +4 ± 15 N m greater in visit 1 vs visit 2 at the main effect level. The MDC_{95} for this measure was 14 N m, 95 % of the cohort could be considered meaningfully changed beyond chance. EFP_{180} only differed when the main effect of Condition ($F_{(1,19)} = 9.1$, p = .007, $\eta p^2 = 0.32$) was examined. There was no difference in EFP_{180} for all other main or interaction effects. EFP_{180} was +8 ± 12 N m greater HEAT vs CONT. EFP_{300} differed for the main effect of Condition only ($F_{(3,57)} = 5.6$, p = .002, $\eta p^2 = 0.23$). EFP_{300} was +5 ± 10 N m greater in HEAT vs CONT at the main effect level. $EFP_{25\ \%}$ differed for the main effect of Visit only ($F_{(1,19)} = 4.8$, p = .041, $\eta p^2 = 0.20$). $EFP_{25\ \%}$ was +16

Table 2
Physiological and perceptual responses to 90 min of passive thigh heating between two visits and averaged between visits (n = 20). Data are mean ± SD; **p* < .05 vs control at corresponding timepoint; #*p* < .05 vs baseline (0 min); ^ *denotes difference between condition p* < .05, † *denotes difference between visit p* < .05. *SBP: Systolic blood pressure; DBP: Diastolic blood pressure; MAP: Mean arterial pressure.*

	0 min	30 min	60 min	90 min
Visit 1				
Heart rate (b.min^{-1})	75 ± 14	81 ± 13	81 ± 11	81 ± 13
SBP (mmHg)	125 ± 20	116 ± 8	117 ± 11	120 ± 15
DBP (mmHg) †	74 ± 10	71 ± 10	70 ± 8	68 ± 7 #
MAP (mmHg)	91 ± 12	86 ± 8	86 ± 8	85 ± 8
RPE (HEAT) ^	13 ± 2	15 ± 1	15 ± 2	16 ± 2
RPE (CONT)	15 ± 1	16 ± 1	16 ± 2	17 ± 2
Thermal sensation	4.0 ± 0.7	5.0 ± 0.6	5.2 ± 0.7	5.2 ± 1.0
Visit 2				
Heart rate (b.min^{-1})	74 ± 11	81 ± 9	80 ± 10	79 ± 10
SBP (mmHg)	123 ± 15	115 ± 13	118 ± 15	119 ± 12
DBP (mmHg) †	71 ± 10	68 ± 9	69 ± 10	68 ± 8
MAP (mmHg)	88 ± 11	83 ± 10	85 ± 9	85 ± 8
RPE (HEAT) ^	14 ± 1	15 ± 2	15 ± 2	15 ± 2
RPE (CONT)	15 ± 1	16 ± 2	17 ± 2	17 ± 2
Thermal sensation	3.5 ± 0.8	4.7 ± 0.6	5.1 ± 0.5	5.2 ± 0.6
Mean				
Heart rate (b.min^{-1})	74 ± 11	81 ± 9 #	81 ± 9 #	80 ± 10
SBP (mmHg)	125 ± 17	116 ± 9 #	118 ± 12 #	119 ± 13
DBP (mmHg)	73 ± 6	70 ± 4	70 ± 5	68 ± 4 #
MAP (mmHg)	90 ± 10	84 ± 8 #	86 ± 8 #	85 ± 7 #
RPE (HEAT) ^	14 ± 1 *	15 ± 1 *#	15 ± 1 *#	16 ± 1 *#
RPE (CONT)	15 ± 1	16 ± 1 #	16 ± 1 #	17 ± 1 #
Thermal sensation	3.8 ± 0.6	4.8 ± 0.4	5.2 ± 0.4	5.2 ± 0.5

Table 3

Mean ± SD Peak torque and peak velocity (left) and early force production (torque at 0.18 s), early velocity production (centre) and rate of force development at 50ms (right) generated at 60°/s, 180°/s and 300°/s and *vs.* 25 % of MVIC force in heated (HEAT) and control (CONT) legs across 90 min of passive thigh heating separated by visit and averaged between visits (n = 20). **p < .05 vs control at corresponding timepoint; #p < .05 vs baseline* (0 min)*; ˆ denotes main effect difference between condition p < .05, † denotes difference between visit p < .05*

	0 min	30 min	60 min	90 min		0 min	30 min	60 min	90 min		0 min	30 min	60 min	90 min
Visit 1	Isokinetic Contractions - Peak torque (N.m)					Isokinetic Contractions - EFP (N.m)					Isokinetic Contractions – RFD$_{50}$ (N.m.s^{-1})			
60°/s (HEAT)	186 ± 62	189 ± 71	191 ± 72	187 ± 66	60°/s (HEAT)	124 ± 55	150 ± 68	154 ± 62	153 ± 66	60°/s (HEAT) †	988 ± 534	1229 ± 550	1296 ± 502	1255 ± 496
60°/s (CONT)	175 ± 56	176 ± 63	174 ± 63	170 ± 59	60°/s (CONT)	129 ± 56	139 ± 47	143 ± 54	142 ± 52	60°/s (CONT)	1280 ± 436	1283 ± 499	1280 ± 420	1323 ± 598
180°/s (HEAT)	132 ± 50	143 ± 56	144 ± 52	142 ± 50	180°/s (HEAT)	123 ± 50	132 ± 53	135 ± 52	133 ± 49	180°/s (HEAT) †	824 ± 532	954 ± 520	1083 ± 577	1053 ± 521
180°/s (CONT)	133 ± 45	133 ± 43	132 ± 42	131 ± 48	180°/s (CONT)	123 ± 43	122 ± 38	125 ± 42	121 ± 44	180°/s (CONT)	1106 ± 535	1137 ± 571	1114 ± 506	1135 ± 568
300°/s (HEAT) †	105 ± 38	114 ± 45	114 ± 45	114 ± 45	300°/s (HEAT)	94 ± 34	95 ± 34	94 ± 31	96 ± 34	300°/s (HEAT) †	460 ± 506	600 ± 494	614 ± 507	601 ± 475
300°/s (CONT) †	105 ± 38	105 ± 38	103 ± 36	103 ± 37	300°/s (CONT)	90 ± 30	92 ± 33	91 ± 30	87 ± 30	300°/s (CONT) †	650 ± 448	651 ± 537	719 ± 473	717 ± 477
	Isotonic Contractions - Peak velocity (°/s)					Isotonic Contractions - EVP (°/s)					Isotonic Contractions - RFD (N.m.s^{-1})			
25 % MVIC (HEAT) †	403 ± 47	398 ± 50	400 ± 53	400 ± 54	25 % MVIC (HEAT) †	362 ± 72	354 ± 70	346 ± 70	365 ± 66	25 % MVIC (HEAT)	290 ± 210	301 ± 197	319 ± 170	303 ± 161
25 % MVIC (CONT) †	393 ± 39	394 ± 49	391 ± 51	392 ± 56	25 % MVIC (CONT) †	381 ± 57	367 ± 58	369 ± 55	366 ± 58	25 % MVIC (CONT)	295 ± 165	356 ± 228	301 ± 210	272 ± 174
Visit 2	Isokinetic Contractions - Peak torque (N.m)					Isokinetic Contractions - EFP (N.m)					Isokinetic Contractions – RFD$_{50}$ (N.m.s^{-1})			
60°/s (HEAT)	176 ± 62	184 ± 70	179 ± 67	182 ± 68	60°/s (HEAT)	144 ± 62	155 ± 64	155 ± 60	152 ± 69	60°/s (HEAT)	1105 ± 376	1153 ± 394	1158 ± 366	1128 ± 312
60°/s (CONT)	164 ± 54	164 ± 59	167 ± 57	167 ± 60	60°/s (CONT)	141 ± 57	140 ± 55	142 ± 58	146 ± 58	60°/s (CONT)	1150 ± 356	1074 ± 362	1115 ± 364	1138 ± 349
180°/s (HEAT)	139 ± 50	140 ± 51	141 ± 51	142 ± 52	180°/s (HEAT)	133 ± 49	135 ± 48	136 ± 50	135 ± 50	180°/s (HEAT)	841 ± 523	853 ± 423	903 ± 422	876 ± 427
180°/s (CONT)	131 ± 45	130 ± 47	127 ± 44	131 ± 44	180°/s (CONT)	127 ± 42	127 ± 43	125 ± 41	128 ± 43	180°/s (CONT)	1042 ± 484	954 ± 474	978 ± 472	1035 ± 508
300°/s (HEAT)	110 ± 40	110 ± 39	112 ± 40	111 ± 38	300°/s (HEAT)	99 ± 38	90 ± 41	93 ± 36	90 ± 38	300°/s (HEAT)	493 ± 435	498 ± 353	467 ± 409	534 ± 401
300°/s (CONT)	107 ± 36	99 ± 41	106 ± 36	109 ± 38	300°/s (CONT)	90 ± 30	86 ± 31	86 ± 29	86 ± 32	300°/s (CONT)	581 ± 414	553 ± 427	596 ± 460	602 ± 487
	Isotonic Contractions - Peak velocity (°/s)					Isotonic Contractions - EVP (°/s)					Isotonic Contractions - RFD (N.m.s^{-1})			
25 % MVIC (HEAT)	410 ± 49	404 ± 44	404 ± 51	399 ± 52	25 % MVIC (HEAT)	328 ± 64	330 ± 89	353 ± 74	354 ± 64	25 % MVIC (HEAT)	324 ± 228	313 ± 148	339 ± 178	311 ± 179
25 % MVIC (CONT)	397 ± 41	396 ± 48	394 ± 44	404 ± 50	25 % MVIC (CONT)	358 ± 44	367 ± 56	357 ± 60	354 ± 60	25 % MVIC (CONT)	267 ± 210	306 ± 232	233 ± 174	272 ± 157
Mean	Isokinetic Contractions - Peak torque (N.m)					Isokinetic Contractions - EFP (N.m)					Isokinetic Contractions – RFD$_{50}$ (N.m.s^{-1})			
60°/s (HEAT) ˆ	180 ± 60	185 ± 67 *	184 ± 66 *	185 ± 65 *	60°/s (HEAT)	134 ± 57	153 ± 66 #	154 ± 61 *#	153 ± 67 #	60°/s (HEAT) ˆ	1134 ± 469	1256 ± 511*#	1288 ± 444*#	1289 ± 535*#
60°/s (CONT)	170 ± 51	170 ± 57	170 ± 56	169 ± 57	60°/s (CONT)	135 ± 54	139 ± 49	142 ± 55	144 ± 54	60°/s (CONT)	1127 ± 356	1113 ± 356	1137 ± 357	1133 ± 316
180°/s (HEAT) ˆ	133 ± 49	140 ± 51 *	141 ± 50 *	140 ± 51 *	180°/s (HEAT) ˆ	128 ± 49	134 ± 50	135 ± 50	134 ± 49	180°/s (HEAT) ˆ	965 ± 514	1045 ± 537*	1098 ± 525*#	1094 ± 530*#
180°/s (CONT)	130 ± 42	130 ± 42	130 ± 42	129 ± 42	180°/s (CONT)	125 ± 42	125 ± 40	125 ± 41	124 ± 43	180°/s (CONT)	942 ± 488	904 ± 426	940 ± 430	956 ± 450
300°/s (HEAT) ˆ	106 ± 38	110 ± 41 *	111 ± 41 *	111 ± 41 *#	300°/s (HEAT) ˆ	96 ± 36	93 ± 36	93 ± 33	93 ± 35	300°/s (HEAT)	555 ± 441	625 ± 507	667 ± 478	659 ± 462
300°/s (CONT)	104 ± 36	100 ± 35	103 ± 35	105 ± 38	300°/s (CONT)	90 ± 29	89 ± 31	88 ± 29	87 ± 30	300°/s (CONT)	537 ± 416	526 ± 380	532 ± 425	568 ± 438
	Isotonic Contractions - Peak velocity (°/s)					Isotonic Contractions - EVP (°/s)					Isotonic Contractions - RFD (N.m.s^{-1})			
25 % MVIC (HEAT)	405 ± 47	400 ± 45	399 ± 49	399 ± 48	25 % MVIC (HEAT)	371 ± 61	361 ± 61	357 ± 58	365 ± 56	25 % MVIC (HEAT)	292 ± 148	328 ± 179	310 ± 179	287 ± 134
25 % MVIC (CONT)	393 ± 39	392 ± 46	392 ± 45	396 ± 49	25 % MVIC (CONT)	343 ± 51	349 ± 66	355 ± 62	354 ± 59	25 % MVIC (CONT)	296 ± 152	310 ± 148	286 ± 125	292 ± 125

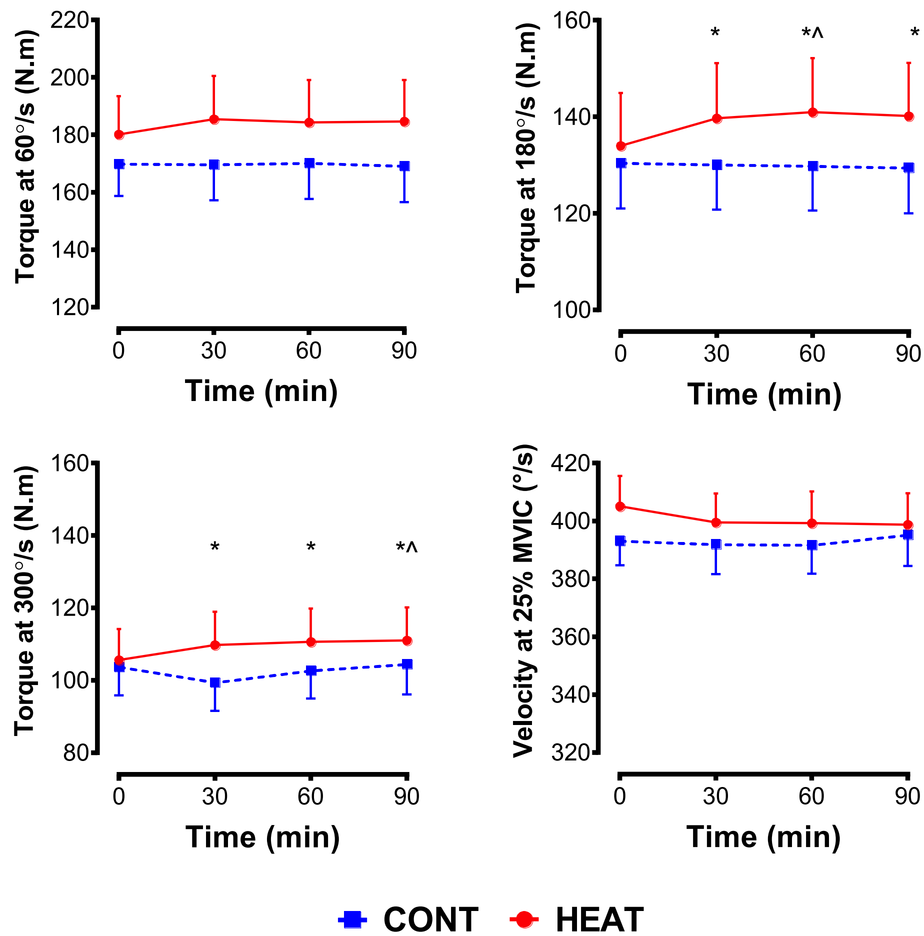

Fig. 3. Mean ± SE Change in peak force production 60, 180, 300°/s and maximum velocity, over 90 min of passive thigh heating. * *denotes significant difference between HEAT (red circles) and CONT (blue square) at corresponding timepoint (p < .05). ^ denotes significant difference from baseline (p < .05).*

± 27°/s greater in Visit 2 vs Visit 1 at the main effect level.

3.2.5. *Perceptual measures following upper thigh muscle hyperthermia*

Rate of perceived exertion differed when the main effects of Condition ($F_{(1,19)} = 15.0$, $p = .001$, $\eta p^2 = 0.44$) and Time ($F_{(3,57)} = 24.0$, $p = <0.001$, $\eta p^2 = 0.56$) was examined. Thermal sensation differed when the main effect of Time ($F_{(3,57)} = 48.6$, $p < .001$, $= \eta p^2.72$), see Table 2. In response to the global rate of change scale, 80 % of participants self-reported that heating made them feel at least "a little bit better" in terms of readiness for exercise, 50 % self-reported that heating made them feel at least "moderately better" in terms of readiness for exercise and 35 % self-reported that heating made them feel at least "a great deal better" in terms of readiness for exercise.

4. Discussion

This is the first study to evaluate the inter and intraday reliability of knee extensor torque production across a variety of contractile speeds and physiological responses at multiple timepoints during a passive thigh heating protocol. The peak isokinetic torque values displayed excellent intraday reliability for both the heated and control conditions. Reliability for EFP at all contraction velocities was also excellent while $RFD_{(slow)}$, $RFD_{(mod)}$, $RFD_{(fast)}$, and EVP was moderately reliable whilst $RFD_{(isotonic)}$ displayed low intraday reliability. A poor coefficient of variation was observed within the RFD values; however, this is likely due to the exaggerated difference when torque values are divided by the elapsed time. Although good intraday reliability was observed within the ICC values of the RFD scores, the findings of significant differences between visits for RFD_{slow}, RFD_{mod}, RFD_{fast} may indicate poorer reliability; it is worth noting that this too, may also be exaggerated by the inflating the torque values, and also their differences, by dividing by the elapsed time in seconds. It does not appear that passive hyperthermia negatively influences reliability relative to the control limb, indeed in RFD and EFP measures, reliability was typically superior in the heated vs control limb. Systemic physiological responses i.e., HR, blood pressure and T_{tymp} responses displayed very good reliability with the reliability of local physiological markers i.e., T_{mu} and T_{sk} identified as good. The passive thigh heating intervention increased muscle temperature in the HEAT condition +4.6 °C at 30 min, +5.0 °C at 60 min and +5.3 °C at 90 min, in contrast CONT saw an increase from baseline of only ~1.5 °C after 30 min which was sustained throughout testing. The increase in T_{mu} occurred in the absence of meaningful changes in systemic physiological markers highlighting the localised action of the intervention. This study also quantified the change in isokinetic and isotonic muscle function (peak isokinetic torque, EFP and peak isotonic velocity) following a bout of passive heating relative to a control. To this end, from 30 min onwards heating increased peak torque during moderate contractile speeds by 8 % (+10 N m) and during fast contractile speeds by 10 % (+10 N m) relative to the control. Heating was also found to increase RFD_{50} by 14 % (+155 N m^{-1}) and EFP by 15 % (+20 N m) during the slow contraction speed (60°/s) when compared to baseline and the control. To contextualise the magnitudes of change observed in response to the heating intervention in this study, large effect sizes ($>\eta p^2.14$) were observed in peak torque during moderate and fast contractions. Further, the group mean increases in muscle function are also above our calculated MDC in moderate and fast contractions as well as for the EFP at 60°/s, with 65 %, 75 % and 95 % of individuals

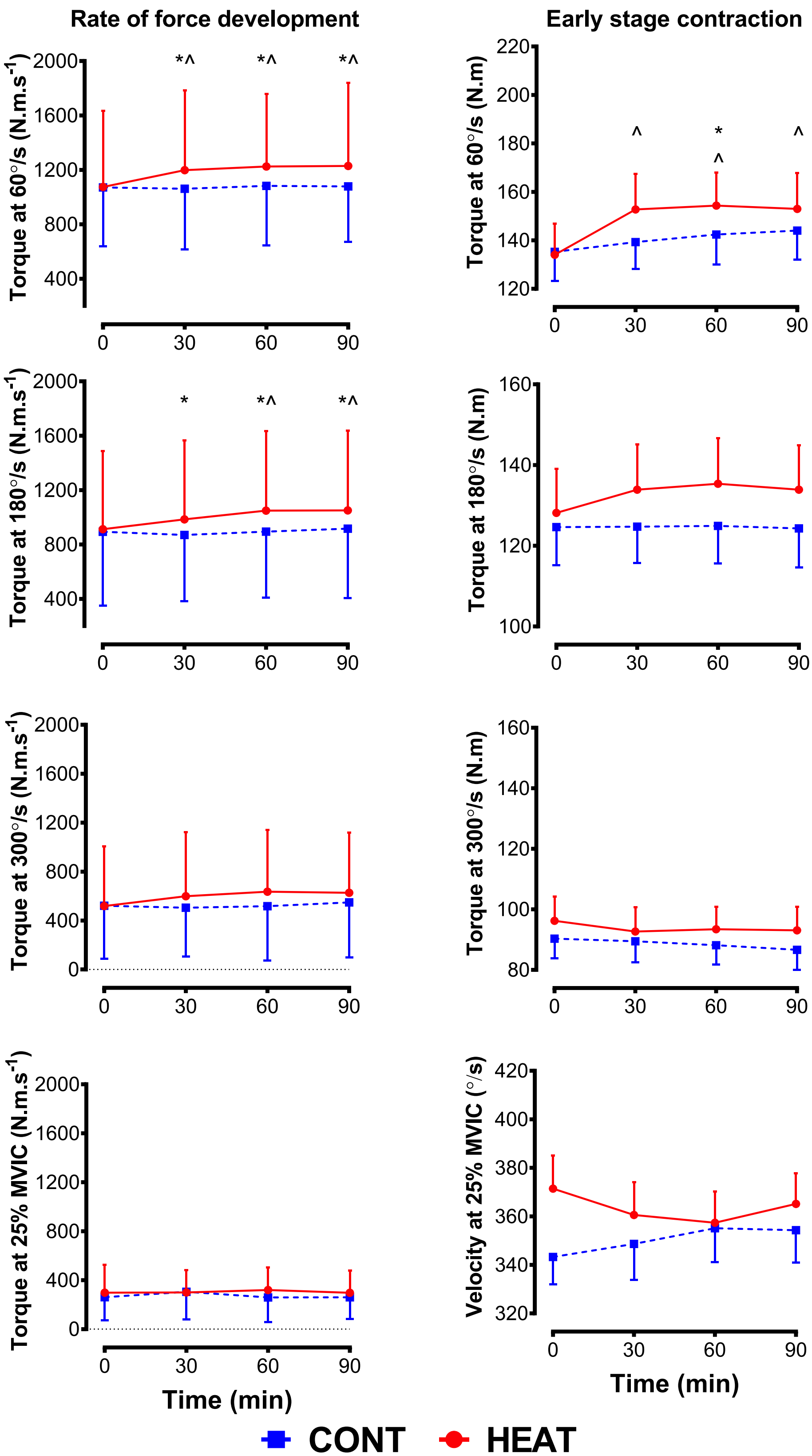

Fig. 4. Mean ± SE Change in rate of force development (left) and early force or velocity production (right) across 60, 180, 300°/s velocity production at 25 % of MVIC force over 90 min of passive thigh heating. ** denotes significant difference between HEAT (red circles) and CONT (blue square) at corresponding timepoint ($p < .05$). ˆ denotes significant difference from baseline ($p < .05$).*

exceeding the calculated MDC thresholds respectively. Large effect sizes (>ηp^2.14) were observed in RFD_{slow}; and the group mean change in RFD_{slow} was also above calculated MDC, 85 % of all individuals exceeded the MDC threshold. It was observed that heating improved "readiness for exercise" and reduced perception of exertion while being a thermally comfortable experience, likely due to the absence of change in systemic physiological responses. In agreement with our hypothesis and adding confidence to the reported ergogenic effects of the intervention, the inter-day repeatability of peak torque during slow, moderate and fast contractions and peak velocity achieved during leg extension exercise following passive heating was excellent according to the ICC testing.

Excellent reliability has been documented when testing isokinetic knee extension (Maffiuletti et al., 2007; Toonstra and Mattacola, 2013), peak torque (Sole et al., 2007) and isotonic contractions (Van Driessche et al., 2018) across days. We now extend this understanding by identifying that isokinetic and isotonic dynamometry following passive heating produces reliable results between days. Our study therefore finds that the addition of heating does not alter reproducibility of peak torque outcomes, maintaining similar intraday reliability to unheated isokinetic dynamometry (Holmbäck and Lexell, 2007; Kambič et al., 2020). When examining similar work investigating the reliability of the RFD during isokinetic exercise (Brown et al., 2005) lower ICC scores (0.58) than the current study (0.84) were observed. A review on RFD reliability reports that ICC scores typically range between 0.8 and 0.9 (Davó and Solana, 2014), whilst the current study is in agreement for the isokinetic trials, the poor reliability of the isotonic trials is unexplained. Further research into the intraday reliability of isokinetic and isotonic RFD measurements, including CV are required. In addition to quantifying the reliability of our protocol, and likely that of others using similar approaches (Rodrigues et al., 2021; Mornas et al., 2022; Chang et al., 2023), a key finding of this study is that passive heating enhanced peak isokinetic torque at moderate (180°/s) and fast (300°/s) contraction velocities. Whilst preliminary research into isometric contractions following hyperthermia have not identified benefits to peak force production (Thornley et al., 2003; Morrison et al., 2004; Rodrigues et al., 2021), increases in early force development i.e. an increased rate of force development (+26 %) at 50 ms have been observed (Rodrigues et al., 2021). Additionally, passive heat exposure has also been reported to accelerate fascicle shortening velocity and improving the rate of force development (+48 %) during the first 100 ms of a voluntary explosive isometric contraction (Mornas et al., 2022). Although there are subtle differences between rate of force production and EFP these results align with our EFP_{60} observations where EFP, an important metric due to its relationship with dynamic physical activities, was enhanced by 20 N.m. (+15 %) in the 60°/s heated condition. This improvement occurred after 30 min of heating and remained in this enhanced state throughout the heated protocol. Increases in EFP likely occurred in the 60°/s contractions only, as this was the only contractile speed slow enough to elicit maximal/near maximal voluntary force production with observation of this phenomenon typically restricted to isometric contractions (Maffiuletti et al., 2016). From a translational perspective, there does not appear to be additional benefit in applying passive thigh heating for 60 and 90 min suggesting that a 30 min intervention may be sufficient to elicit muscle function benefits. Other heating interventions, e.g., whole body heating, may however require extended protocols to elicit equivalent intramuscular responses.

Increasing or preserving elevated muscle temperature, before physical activity has been demonstrated to enhance muscle function (Faulkner et al. 2013a, 2013c). Our findings, which identify that the benefits of heating on peak torque are most pronounced during moderate and faster isokinetic contractions, align with prior sprint cycling studies where greater increases in power output were observed during faster vs slower cadences following lower limb passive heating (Sargeant, 1987). The mechanisms underpinning an increase in moderate and fast isokinetic force production following passive heating remain unclear; however, it has been suggested that in addition to sodium channel activated increases in nerve conduction velocity (Todnem et al., 1989; Kiernan et al., 2001), augmented Ca^{2+} handling occurs (Kobayashi et al., 2005). Increased intramuscular temperature elevates Ca^{2+} storage reserve in the sarcoplasmic reticulum (Godt and Lindley, 1982; Ranatunga, 1984; Kobayashi et al., 2005), which then simulates the SERCA pump to increase Ca^{2+}movement into and out of the working muscle (Davies and Young, 1983). This alteration reduces half-relaxation time and increases muscle shortening velocity and force production (Rodrigues et al., 2022). An increase in intramuscular fluid has also been suggested to be an important element associated with enhanced muscular function by stiffening the muscle-tendon unit (Eng et al., 2018). The increased fluid within the epimysium and perimysium within the fixed area of the muscle increases muscle stiffness allowing for a more efficient transfer of force (Hughes et al., 2015) . Whilst heating is known to influence metabolic systems within the muscle (Girard et al., 2015; Brocherie et al., 2024) this response is unlikely to be a factor in short periods of maximal exercise as investigated within this study. While the fastest isokinetic contraction (300°/s) saw the greatest benefit supporting this mechanism, in contrast isotonic velocity did not see any improvement; despite being the fastest contractile velocity assessed within the experiment (415 ± 50°/s). The null response in isotonic contractions may be explained in part by the velocity limiting factor of ATP disassociation from the myosin head (Nyitrai et al., 2006) and decreases in passive muscle and active tendon stiffness which result in unchanged late and global rates of force development (Mornas et al., 2022).

Systemic physiological responses, particularly T_{tymp} were unmeaningfully changed displayed excellent reliability, suggesting that the passive thigh heating protocol did not increase core temperature or lead to cardiovascular strain. In addition to removing the known performance impairment associated with whole body hyperthermia (Thomas et al., 2006), minimizing increases in core temperature reduces the potential for hypotension induced syncope or other negative events associated with hyperthermia. Muscle temperature in the heated condition demonstrated good reliability with the absolute (37–38 °C) and relative (+4–6 °C) increase in muscle temperature consistent with other research using water perfused garments (Ihsan et al., 2020; Koch et al., 2021; Gibson et al., 2023), and similar to changes observed during exercise (Kenny et al., 2003; Gibson et al., 2014; Kapnia et al., 2023). Our observed peak muscle temperature likely signals the attainment of a physiological plateau in response to this particular intervention, as the temperature gradient between the muscle and core temperature diminishes, and the heating impulse decreases concurrently with increased intramuscular blood flow (Heinonen et al., 2011; Koch et al., 2021). Only when core temperature increases above this apparent plateau does muscle temperature appear to increase further during passive hyperthermia (Watanabe et al., 2024). To achieve higher temperatures, alternative heating interventions such as diathermy are likely necessary, although at the current time it remains unknown whether increasing skeletal muscle temperature above the magnitudes observed in this study would elicit greater increases in muscle function. From a perceptual perspective, when asked how the heated leg felt compared to the control leg in terms of "readiness for exercise" most respondents reported that heating improved their perceived readiness for exercise by at least "a little bit". The heated condition saw increases in force production but a decrease in a rating for perceived exertion, this may be linked to the analgesic effect of heating (Malanga et al., 2015). The reported enhancement in "readiness for exercise" underscores the potential of localised heating as a preparatory strategy for physical activity that does not undesirably perturb systemic physiology.

The findings from this study have practical implications across various fields, particularly in sports performance, physical therapy, and geriatrics. Traditional active warmups have been demonstrated to not improve isokinetic force at 60°/s, 180°/s or 300°/s (Park et al., 2018; Rodrigues et al., 2020a) and may have reduced intramuscular pressure and stiffness as measured by an increase in mechanomyographic signals

(Altamirano et al., 2012). The demonstrated reliability of muscle function and physiological responses following passive heating suggests that this method could be integrated into warm-up routines for athletes to enhance performance and used in conjunction with in-competition heat maintenance strategies (Faulkner et al., 2013b; Raccuglia et al., 2015). The increase in peak torque and EFP, especially at moderate and fast contraction speeds, highlights that passive heating an effective strategy for improving muscle force production before activities requiring high/maximal exertion e.g., athletic competition. The increases in muscular force presented in this study (+10 N m, 8 %) provides similar benefits to widely used performance aids such as caffeine (+5 N m, 3 %) (Grgic et al., 2022) and L-arginine (+4.2 %) (Zart et al., 2023) and may therefore be considered a surrogate or complement to other interventions that are designed to improve muscle function. Additionally, the protocol could benefit individuals in physical therapy settings, where the combination of increased muscle function and reduced perceived exertion could accelerate recovery while minimizing pain. The use of this approach as a non-invasive, thermally comfortable, and ergogenic intervention strategy adds significant value to pre-exercise and therapeutic protocols, including as a part of late-stage rehabilitation protocols as a means to accelerate training adaptations via optimised molecular responses. Finally, passive preheating may be useful for older adults who are unable to conduct a traditional warm-up prior to physical activity such as climbing stairs or walking.

This research provides further foundations to continue research into the effects of passive heating on muscle function in other cohorts e.g., older adults, and contexts e.g., physical therapy and rehabilitation. As previously discussed, the mechanisms that underpin the augmentation of muscle function following heating are largely unknown specifically pathways associated with early vs peak force production require delineation. This study may therefore guide future work investigating the underlying mechanisms of passive heating's ergogenic potential by providing insights across different contractile types and speeds, tested at the same muscle temperature across multiple timepoints. Heated resistance exercise is also an emerging field of study (Casadio et al., 2017; Pryor et al., 2024), accordingly the heating methodology used in this study may be implemented within a resistance based exercise regime to optimise adaptation. Some potential limitations of this experimental design include a lack of familiarisation to the protocol as well as a potential inconsistent motivation between sets and days influencing effort. However, this may not be a relevant concern relating to our serial measurements as evidenced by maintained performance and equal or lowering CV values throughout the protocol. This study is limited in its analysis of RFD_{50} due to the 100HZ export rate from the Biodex restricting the precision of the calculation. The serial muscle function measures within this study also modestly increased muscle temperature in the control leg from baseline every 30 min, thus did not simulate how heating may attenuate the decline in muscle function that may be incurred following long periods of true sedentary behaviour. Previous research on prolonged passive heating observed decreases in muscle temperature in the control condition over time, likely due to the absence of physical activity (Gibson et al., 2023). It could therefore be postulated that passive heating would have an even greater effect when assessed against inactive and normothermic musculature. This study also only focused on a young healthy population, and did not measure the retention/decay of increased muscle function post cessation of heating. Future research should investigate the mechanisms underpinning the observed changes following heating and explore different how heating modalities, timings and conditions affect muscle function across a variety of populations. Finally research exploring how heating may counteract longer acute sedentary muscle function deterioration could provide useful as the general population spends multiple hours sedentary.

5. Conclusion

In summary, peak isokinetic and isotonic muscle function, isokinetic EFP and RFD, local thigh temperature and systemic physiological responses following passive upper thigh heating produce highly reliable outcomes between days. Passive heating of the thigh for 30 min increased muscle temperature by 4.6 °C which enhanced peak isokinetic force during moderate and fast contractile velocities by ~10 %. Whilst the unheated (control) leg remained unchanged from baseline, a 14 % increase in the rate of force development was observed in the heated leg, with heating facilitating a 15 % increase in early force production, both during the slow isokinetic contractions only.

CRediT authorship contribution statement

Desmond Denny: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel C. Low:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Oliver R. Gibson:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Data availability

The datasets used and/or analysed during the current study are available here https://figshare.com/s/b1493067f473fa66a718 (https://doi.org/10.17633/rd.brunel.28303022).

Funding sources

There are no external funding sources associated with this project.

Declaration of competing interest

There are no competing interests associated with this project.

Acknowledgements

The authors would like to thank the participants for volunteering to participate in the experiment and Amelia Dingley and Alishia Rockson for technical support with the study.

Data availability

No

References

Altamirano, K.M., Coburn, J.W., Brown, L.E., Judelson, D.A., 2012. Effects of warm-up on peak torque, rate of torque development, and electromyographic and mechanomyographic signals. J. Strength Condit Res. 26, 1296–1301. https://doi.org/10.1519/JSC.0B013E31822E7A85.

Amaral, G.M., Marinho, H.V.R., Ocarino, J.M., et al., 2014. Muscular performance characterization in athletes: a new perspective on isokinetic variables. Braz. J. Phys. Ther. 18, 521. https://doi.org/10.1590/BJPT-RBF.2014.0047.

Baracos, V.E., Wilson, E.J., Goldberg, A.L., 1984. Effects of temperature on protein turnover in isolated rat skeletal muscle. https://doi.org/10.1152/AJPCELL.1984.246.1.C125.

Bergh, U., Ekblom, B., 1979. Influence of muscle temperature on maximal muscle strength and power output in human skeletal muscles. Acta Physiol. Scand. 107, 33–37. https://doi.org/10.1111/j.1748-1716.1979.tb06439.x.

Bishop, D., 2003. Warm up I: potential mechanisms and the effects of passive warm up on exercise performance. Sports Med. 33, 439–454. https://doi.org/10.2165/00007256-200333060-00005/FIGURES/8.

Blazquez, I.N., Warren, B.L., O'hanlon, A.M., Silvestri, L.R., 2013. An adequate interset rest period for strength recovery during a common isokinetic test. J. Strength Condit Res. 27, 1981–1987. https://doi.org/10.1519/JSC.0B013E3182764D70.

Bobos, P., Ziebart, C., Furtado, R., et al., 2020. Psychometric properties of the global rating of change scales in patients with low back pain, upper and lower extremity disorders. A systematic review with meta-analysis. J. Orthop. 21, 40–48. https://doi.org/10.1016/J.JOR.2020.01.047.

Borg, D.N., Bach, A.J.E., O'Brien, J.L., Sainani, K.L., 2022. Calculating sample size for reliability studies. PM&R 14, 1018–1025. https://doi.org/10.1002/PMRJ.12850.

Borg, G., 1990. Psychophysical scaling with applications in physical work and the perception of exertion. Scand. J. Work. Environ. Health 16, 55–58. https://doi.org/10.5271/sjweh.1815.

Brocherie, F., Girard, O., Mornas, A., et al., 2024. "Citius, altius, fortius" in the face of global warming: not as simple as it seems. npj Climate and Atmospheric Science 7 (1 7), 1–2. https://doi.org/10.1038/s41612-024-00774-3, 2024.

Brown, L.E., Whitehurst, M., Findley, B.W., 2005. Reliability of rate of velocity development and phase measures on an isokinetic device. J. Strength Condit Res. 19, 189–192. https://doi.org/10.1519/R-15004.1.

Chang, Y., Liu, X., Hurr, C., 2023. Local passive heating administered during recovery impairs subsequent isokinetic knee extension exercise performance. Isokinet. Exerc. Sci. 31, 103–112. https://doi.org/10.3233/IES-220030.

Cheng, A.J., Rice, C.L., 2005. Fatigue and recovery of power and isometric torque following isotonic knee extensions. J. Appl. Physiol. 99, 1446–1452. https://doi.org/10.1152/JAPPLPHYSIOL.00452.2005/ASSET/IMAGES/LARGE/ZDG0100561130003.JPEG.

Cheung, S.S., Sleivert, G.C., 2004. Lowering of skin temparature decreases isokinetic maximal force production independent of core temperature. Eur. J. Appl. Physiol. 91, 723–728. https://doi.org/10.1007/S00421-004-1062-0/FIGURES/3.

Davies, C.T.M., Young, K., 1983. Effect of temperature on the contractile properties and muscle power of triceps surae in humans. https://doi.org/10.1152/JAPPL.1983.55.1.191.

Davó, J.L.H., Solana, R.S., 2014. Rate of force development: reliability, improvements and influence on performance. A review. European Journal of Human Movement.

de Araujo Ribeiro Alvares, J.B., Rodrigues, R., de Azevedo Franke, R., et al., 2015. Inter-machine reliability of the Biodex and Cybex isokinetic dynamometers for knee flexor/extensor isometric, concentric and eccentric tests. Phys. Ther. Sport 16, 59–65. https://doi.org/10.1016/J.PTSP.2014.04.004.

Dontje, M.L., Dall, P.M., Skelton, D.A., et al., 2018. Reliability, minimal detectable change and responsiveness to change: indicators to select the best method to measure sedentary behaviour in older adults in different study designs. PLoS One 13. https://doi.org/10.1371/JOURNAL.PONE.0195424.

Draper, D.O., Knight, K., Fujiwara, T., Castel, J.C., 1999. Temperature change in human muscle during and after pulsed short-wave diathermy. J. Orthop. Sports Phys. Ther. 29, 13–22. https://doi.org/10.2519/JOSPT.1999.29.1.13.

Durnin, J.V., Womersley, J. V.G.A., 1974. Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. British journal of nutrition 32 (1), 77–97.

Eng, C.M., Azizi, E., Roberts, T.J., 2018. Structural determinants of muscle gearing during dynamic contractions. Integr. Comp. Biol. 58, 207–218. https://doi.org/10.1093/ICB/ICY054.

Essig, D.A., Segal, S.S., White, T.P., 1985. Skeletal muscle protein synthesis and degradation in vitro: effects of temperature. https://doi.org/10.1152/AJPCELL.1985.249.5.C464.

Faulkner, S.H., Ferguson, R.A., Gerrett, N., et al., 2013a. Reducing muscle temperature drop after warm-up improves sprint cycling performance. Med. Sci. Sports Exerc. 45, 359–365. https://doi.org/10.1249/MSS.0B013E31826FBA7F.

Faulkner, S.H., Ferguson, R.A., Gerrett, N., et al., 2013b. Reducing muscle temperature drop after warm-up improves sprint cycling performance. Med. Sci. Sports Exerc. 45, 359–365. https://doi.org/10.1249/MSS.0b013e31826fba7f.

Faulkner, S.H., Ferguson, R.A., Hodder, S.G., Havenith, G., 2013c. External muscle heating during warm-up does not provide added performance benefit above external heating in the recovery period alone. Eur. J. Appl. Physiol. 113, 2713–2721. https://doi.org/10.1007/S00421-013-2708-6/TABLES/3.

Feiring, D.C., Ellenbecker, T.S., Derscheid, G.L., 1990. Test-Retest Reliability of the Biodex Isokinetic Dynamometer, pp. 298–300. https://doi.org/10.2519/JOSPT.1990.11.7.298.

Gibson, O.R., Astin, R., Puthucheary, Z., et al., 2023. Skeletal muscle angiogenic, regulatory, and heat shock protein responses to prolonged passive hyperthermia of the human lower limb. Am. J. Physiol. Regul. Integr. Comp. Physiol. 324, R1–R14. https://doi.org/10.1152/AJPREGU.00320.2021.

Gibson, O.R., Dennis, A., Parfitt, T., et al., 2014. Extracellular Hsp72 concentration relates to a minimum endogenous criteria during acute exercise-heat exposure. Cell Stress Chaperones 19, 389–400. https://doi.org/10.1007/S12192-013-0468-1.

Girard, O., Brocherie, F., Bishop, D.J., 2015. Sprint performance under heat stress: a review. Scand. J. Med. Sci. Sports 25, 79–89. https://doi.org/10.1111/SMS.12437.

Godt, R.E., Lindley, B.D., 1982. Influence of temperature upon contractile activation and isometric force production in mechanically skinned muscle fibers of the frog. J. Gen. Physiol. 80, 279–297. https://doi.org/10.1085/JGP.80.2.279.

Grbic, V., Djuric, S., Knezevic, O.M., et al., 2017. A novel two-velocity method for elaborate isokinetic testing of knee extensors. Int. J. Sports Med. 38, 741–746. https://doi.org/10.1055/S-0043-113043/ID/R5938-0016/BIB.

Grgic, J., Venier, S., Mikulic, P., 2022. Examining the effects of caffeine on isokinetic strength, power, and endurance. J Funct Morphol Kinesiol 7, 71. https://doi.org/10.3390/JFMK7040071.

Heinonen, I., Brothers, R.M., Kemppainen, J., et al., 2011. Local heating, but not indirect whole body heating, increases human skeletal muscle blood flow. J. Appl. Physiol. 111, 818. https://doi.org/10.1152/JAPPLPHYSIOL.00269.2011.

Hernández-Davó, J.L., Sabido, R., 2014. Rate of force development: reliability, improvements and influence on performance. A review. European Journal of Human Movement 33, 46–69.

Holmbäck, A.M., Lexell, J., 2007. Reproducibility of isokinetic ankle dorsiflexor strength and fatigue measurements in healthy older subjects. Isokinet. Exerc. Sci. 15, 263–270. https://doi.org/10.3233/IES-2007-0282.

Hughes, D.C., Wallace, M.A., Baar, K., 2015. Effects of aging, exercise, and disease on force transfer in skeletal muscle. American Journal of Physiology-Endocrinology and Metabolism 309 (1), E1–E10.

Ihsan, M., Deldicque, L., Molphy, J., et al., 2020. Skeletal muscle signaling following whole-body and localized heat exposure in humans. Front. Physiol. 11, 839. https://doi.org/10.3389/FPHYS.2020.00839/BIBTEX.

Ivy, J.L., Withers, R.T., Brose, G., et al., 1981. Isokinetic contractile properties of the quadriceps with relation to fiber type. Eur. J. Appl. Physiol. Occup. Physiol. 47, 247–255. https://doi.org/10.1007/BF00422470/METRICS.

Jackman, J.S., Bell, P.G., Van Someren, K., et al., 2023. Effect of hot water immersion on acute physiological responses following resistance exercise. Front. Physiol. 14, 1213733. https://doi.org/10.3389/FPHYS.2023.1213733/BIBTEX.

Kambič, T., Lainščak, M., Hadžić, V., 2020. Reproducibility of isokinetic knee testing using the novel isokinetic SMM iMoment dynamometer. PLoS One 15, e0237842. https://doi.org/10.1371/JOURNAL.PONE.0237842.

Kapnia, A., Dallas, C.N., Gerodimos, V., Flouris, A.D., 2023. Impact of warm-up on muscle temperature and athletic performance. Res. Q. Exerc. Sport 94, 460–465. https://doi.org/10.1080/02701367.2021.2007212.

Kenny, G.P., Reardon, F.D., Zaleski, W., et al., 2003. Muscle temperature transients before, during, and after exercise measured using an intramuscular multisensor probe. J. Appl. Physiol. 94, 2350–2357. https://doi.org/10.1152/JAPPLPHYSIOL.01107.2002/ASSET/IMAGES/LARGE/DG0632364005.JPEG.

Kiernan, M.C., Cikurel, K., Bostock, H., 2001. Effects of temperature on the excitability properties of human motor axons. Brain 124, 816–825. https://doi.org/10.1093/BRAIN/124.4.816.

Kim, K., Monroe, J.C., Gavin, T.P., Roseguini, B.T., 2020a. Local heat therapy to accelerate recovery after exercise-induced muscle damage. Exerc. Sport Sci. Rev. 48, 163. https://doi.org/10.1249/JES.0000000000000230.

Kim, K., Reid, B.A., Casey, C.A., et al., 2020b. Effects of repeated local heat therapy on skeletal muscle structure and function in humans. J. Appl. Physiol. 128, 483–492. https://doi.org/10.1152/JAPPLPHYSIOL.00701.2019, 1985.

Kobayashi, T., Goto, K., Kojima, A., et al., 2005. Possible role of calcineurin in heating-related increase of rat muscle mass. Biochem. Biophys. Res. Commun. 331, 1301–1309. https://doi.org/10.1016/J.BBRC.2005.04.096.

Koch, Esteves N., Gibson, OliverR., Khir, A., González-Alonso, J., 2021. Regional thermal hyperemia in the human leg: evidence of the importance of thermosensitive mechanisms in the control of the peripheral circulation. Phys. Rep. 9, e14953. https://doi.org/10.14814/PHY2.14953.

Koo, T.K., Li, M.Y., 2016. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. J Chiropr Med 15, 155. https://doi.org/10.1016/J.JCM.2016.02.012.

Maffiuletti, N.A., Aagaard, P., Blazevich, A.J., et al., 2016. Rate of force development: physiological and methodological considerations. Eur. J. Appl. Physiol. 116 (6 116), 1091–1116. https://doi.org/10.1007/S00421-016-3346-6, 2016.

Maffiuletti, N.A., Bizzini, M., Desbrosses, K., et al., 2007. Reliability of knee extension and flexion measurements using the Con-Trex isokinetic dynamometer. Clin. Physiol. Funct. Imag. 27, 346–353. https://doi.org/10.1111/J.1475-097X.2007.00758.X.

Malanga, G.A., Yan, N., Stark, J., 2015. Mechanisms and efficacy of heat and cold therapies for musculoskeletal injury. Postgrad. Med. J. 127, 57–65. https://doi.org/10.1080/00325481.2015.992719.

Marshall, P.W.M., Cross, R., Lovell, R., 2015. Passive heating following the prematch warm-up in soccer: examining the time-course of changes in muscle temperature and contractile function. Phys. Rep. 3. https://doi.org/10.14814/PHY2.12635.

McGorm, H., Roberts, L.A., Coombes, J.S., Peake, J.M., 2018. Turning up the heat: an evaluation of the evidence for heating to promote exercise recovery, muscle rehabilitation and adaptation. Sports Med. 48, 1311–1328. https://doi.org/10.1007/S40279-018-0876-6.

Mitchell, S.M., Trowbridge, C.A., Fincher, A.L., Cramer, J.T., 2008. Effect of diathermy on muscle temperature, electromyography, and mechanomyography. Muscle Nerve 38, 992–1004. https://doi.org/10.1002/MUS.21084.

Molczyk, L., Thigpen, L.K., Eickhoff, J., et al., 1991. Reliability of Testing the Knee Extensors and Flexors in Healthy Adult Women Using a Cybex® II Isokinetic Dynamometer 14, 37–41. https://doi.org/10.2519/JOSPT.1991.14.1.37.

Mornas, A., Racinais, S., Brocherie, F., et al., 2022. Faster early rate of force development in warmer muscle: an in vivo exploration of fascicle dynamics and muscle-tendon mechanical properties. Am. J. Physiol. Regul. Integr. Comp. Physiol. 323, R123–R132. https://doi.org/10.1152/ajpregu.00280.2021.

Morrison, S., Sleivert, G.C., Cheung, S.S., 2004. Passive hyperthermia reduces voluntary activation and isometric force production. Eur. J. Appl. Physiol. 91, 729–736. https://doi.org/10.1007/S00421-004-1063-Z/FIGURES/6.

Nyitrai, M., Rossi, R., Adamek, N., et al., 2006. What limits the velocity of fast-skeletal muscle contraction in mammals? J. Mol. Biol. 355, 432–442. https://doi.org/10.1016/J.JMB.2005.10.063.

Oksa, J., Rintamäki, H., Mäkinen, T., et al., 1996. EMG-activity and muscular performance of lower leg during stretch-shortening cycle after cooling. Acta Physiol. Scand. 157, 71–78. https://doi.org/10.1046/J.1365-201X.1996.452172000.X.

Park, H.K., Jung, M.K., Park, E., et al., 2018. The effect of warm-ups with stretching on the isokinetic moments of collegiate men. J Exerc Rehabil 14, 78. https://doi.org/10.12965/JER.1835210.605.

Raccuglia, M., Lloyd, A., Filingeri, D., et al., 2015. Post-warm-up muscle temperature maintenance: blood flow contribution and external heating optimisation. Eur. J. Appl. Physiol. https://doi.org/10.1007/s00421-015-3294-6.

Ramanauskiene, I., Skurvydas, A., Sipavičiene, S., et al., 2008. Influence of heating and cooling on muscle fatigue and recovery. Medicina 44, 687. https://doi.org/10.3390/MEDICINA44090088, 2008, Vol 44, Page 687.

Ranatunga, K.W., 1984. The force-velocity relation of rat fast- and slow-twitch muscles examined at different temperatures. J Physiol 351, 517–529. https://doi.org/10.1113/JPHYSIOL.1984.SP015260.

Rodrigues, P., Gabellone Hernandez, S., de Macedo Salgueirosa, F., et al., 2020a. Acute effect of three different warm-up protocols on maximal isokinetic strength in young men. Rev Andal Med Deport 13, 5–9. https://doi.org/10.33155/J.RAMD.2018.02.007.

Rodrigues, P., Trajano, G.S., Stewart, I.B., Minett, G.M., 2022. Potential role of passively increased muscle temperature on contractile function. Eur. J. Appl. Physiol. 122, 2153–2162. https://doi.org/10.1007/S00421-022-04991-7/TABLES/1.

Rodrigues, P., Trajano, G.S., Wharton, L., et al., 2021. A passive increase in muscle temperature enhances rapid force production and neuromuscular function in healthy adults. J. Sci. Med. Sport 24, 818–823. https://doi.org/10.1016/J.JSAMS.2021.01.003.

Rodrigues, P., Trajano, G.S., Wharton, L., Minett, G.M., 2020b. Muscle temperature kinetics and thermoregulatory responses to 42 °C hot-water immersion in healthy males and females. Eur. J. Appl. Physiol. 120, 2611–2624. https://doi.org/10.1007/S00421-020-04482-7/FIGURES/6.

Sáenz, A., Avellanet, M., Hijos, E., et al., 2010. Knee isokinetic test-retest: a multicentre knee isokinetic test-retest study of a fatigue protocol undefined.

Sargeant, A.J., 1987. Effect of muscle temperature on leg extension force and short-term power output in humans. Eur. J. Appl. Physiol. Occup. Physiol. 56, 693–698. https://doi.org/10.1007/BF00424812.

Skurvydas, A., Kamandulis, S., Stanislovaitis, A., et al., 2008. Leg immersion in warm water, stretch-shortening exercise, and exercise-induced muscle damage. J. Athl. Train. 43, 592. https://doi.org/10.4085/1062-6050-43.6.592.

Sole, G., Hamrén, J., Milosavljevic, S., et al., 2007. Test-retest reliability of isokinetic knee extension and flexion. Arch. Phys. Med. Rehabil. 88, 626–631. https://doi.org/10.1016/J.APMR.2007.02.006.

Sweet, D.K., Qiao, J.B., Rosbrook, P., Pryor, J.L., 2024. Load-velocity profiles before and after heated resistance exercise. J. Strength Condit Res. 38, 1019–1024. https://doi.org/10.1519/JSC.0000000000004739.

Thomas, M.M., Cheung, S.S., Elder, G.C., Sleivert, G.G., 2006. Voluntary muscle activation is impaired by core temperature rather than local muscle temperature. J. Appl. Physiol. 100, 1361–1369. https://doi.org/10.1152/JAPPLPHYSIOL.00945.2005/ASSET/IMAGES/LARGE/ZDG0040664940006.JPEG.

Thompson, B.J., Ryan, E.D., Herda, T.J., et al., 2014. Age-related changes in the rate of muscle activation and rapid force characteristics. Age 36, 839. https://doi.org/10.1007/S11357-013-9605-0.

Thornley, L.J., Maxwell, N.S., Cheung, S.S., 2003. Local tissue temperature effects on peak torque and muscular endurance during isometric knee extension. Eur. J. Appl. Physiol. 90, 588–594. https://doi.org/10.1007/S00421-003-0927-Y.

Timm, K.E., Gennrich, P., Burns, R., Fyke, D., 1992. The mechanical and physiological performance reliability of selected isokinetic dynamometers. Isokinet. Exerc. Sci. 2, 182–190. https://doi.org/10.3233/IES-1992-2406.

Todnem, K., Knudsen, G., Riise, T., et al., 1989. The non-linear relationship between nerve conduction velocity and skin temperature. J. Neurol. Neurosurg. Psychiatry 52, 497. https://doi.org/10.1136/JNNP.52.4.497.

Toonstra, J., Mattacola, C.G., 2013. Test-retest reliability and validity of isometric knee-flexion and -extension measurement using 3 methods of assessing muscle strength. J. Sport Rehabil. 22. https://doi.org/10.1123/JSR.2013.TR7.

Van Driessche, S., Van Roie, E., Vanwanseele, B., Delecluse, C., 2018. Test-retest reliability of knee extensor rate of velocity and power development in older adults using the isotonic mode on a Biodex System 3 dynamometer. PLoS One 13. https://doi.org/10.1371/JOURNAL.PONE.0196838.

Walter, S.D., Eliasziw, M., Donner, A., The, J.P., 1998. Sample size and optimal designs for reliability studies. Stat. Med. 17, 101–110. https://doi.org/10.1002/(SICI)1097-0258(19980115)17:1<101::AID-SIM727>3.0.CO;2-E.

Watanabe, K., Koch Esteves, N., Gibson, O.R., et al., 2024. Heat-related changes in the velocity and kinetic energy of flowing blood influence the human heart's output during hyperthermia. J Physiol 602, 2227–2251. https://doi.org/10.1113/JP285760.

Webb, P., 1992. Temperatures of skin, subcutaneous tissue, muscle and core in resting men in cold, comfortable and hot conditions. Eur. J. Appl. Physiol. Occup. Physiol. 64, 471–476. https://doi.org/10.1007/BF00625070/METRICS.

Weir, J.P., 2005. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. J. Strength Condit Res. 19, 231–240. https://doi.org/10.1519/15184.1.

West, D.J., Russell, M., Bracken, R.M., et al., 2016. Post-warmup strategies to maintain body temperature and physical performance in professional rugby union players. J. Sports Sci. 34, 110–115. https://doi.org/10.1080/02640414.2015.1040825.

Young, A.J., Sawka, M.N., Epstein, Y., et al., 1987. Cooling different body surfaces during upper and lower body exercise. https://doi.org/10.1152/JAPPL.1987.63.3.1218.

Zart, S., Brachtendorf, M., Becker, S., Fröhlich, M., 2023. Isolated but not combined ergogenic effects of caffeine and L-arginine during an isokinetic knee extension. Front. Nutr. 10, 1303805. https://doi.org/10.3389/FNUT.2023.1303805/BIBTEX.