ORIGINAL ARTICLE

The effects of local muscle temperature on force variability

Matthew M. Mallette[1] · Lara A. Green[1] · Gary J. Hodges[1] · Reno E. Fernley[1] · David A. Gabriel[1] ·
Michael W. R. Holmes[1] · Stephen S. Cheung[1]

Abstract

Purpose Force variability is affected by environmental temperature, but whether the changes are from altered muscle temperature or proprioception are unclear. We tested how forearm muscle warming and cooling affected a force tracking task.
Methods Twelve males and four females completed evoked, maximal, and isometric wrist flexion contractions (0–30% maximal) during thermoneutral-, warm-, and cold-muscle conditions. Forearm muscle temperature was manipulated using neutral (~33 °C), hot (~44 °C), or cold (~13 °C) water circulated through a tube-lined sleeve. Evoked and voluntary contractions were performed before and after thermal manipulations.
Results Thermal manipulations altered contractile properties as evident in the twitch half-relaxation time, rate of force development, and duration (all $P < 0.05$), suggesting that muscle temperature was successfully altered. Changes in surface electromyography of the flexor carpi radialis root-mean-square amplitude and mean power frequency between temperature conditions (all $P < 0.05$) also indicate muscle temperature changes. No changes to root-mean-square error or variance ratio of the force trace were observed with muscle temperature changes (both $P > 0.05$). Muscle temperature changes did not have a consistent effect on coefficient of variation during each plateau of the staircase contraction.
Conclusions Our results suggest that the ability to perform a multi-plateaued isometric force task is not affected by changes to forearm muscle temperature. As the thermal manipulation was limited to the forearm, changes to hand temperature would be minimal, thus, proprioception in the wrist and hand was preserved allowing performance to be maintained. Therefore, modest changes to forearm muscle temperature are not likely to affect force variability if proprioception is maintained.

Keywords Flexor carpi radialis · Force fluctuation · Force steadiness · Manual dexterity · Motor control · Surface electromyography

Abbreviations

CV	Coefficient of variation
sEMG	Surface electromyography
FCR	Flexor carpi radialis
MVC	Maximal voluntary contraction
MPF	Mean power frequency
RMS	Root-mean-square
RMSE	Root-mean-square-error

✉ Stephen S. Cheung
scheung@brocku.ca

[1] Department of Kinesiology, Brock University, 1812 Sir Isaac Brock Way, St. Catharines, ON L2S 3A1, Canada

Introduction

Manual dexterity and object manipulation is a function of both adequate muscular capacity along with the ability to accurately and precisely control muscle force. These aspects of manual function may be affected by changes in local muscle temperature without any changes to whole-body temperature. Local cooling alters muscle contractile characteristics, including a prolonged time to reach peak tension and half-relaxation in evoked contractions, and an overall increase in evoked peak force from repetitive stimulations (Geurts et al. 2004). The effects of cooling on voluntary strength are equivocal, with both reductions in maximal handgrip force (Giesbrecht et al. 1995) or no change in isometric maximal force of the knee extensors (Thornley et al. 2003). However, despite changes in contractile characteristics, cooling may extend muscular endurance in large muscles involved in knee extension

(Thornley et al. 2003) or small muscles of the extremities for finger flexion (Phillips et al. 2017). Overall, any changes in muscle capacity would need compensatory strategies to maintain overall function. For example, Mallette et al. (2018) demonstrated that local forearm cooling resulted in altered motor unit activity to maintain a set force, due to a combination of altered motor unit firing rates and recruitment thresholds.

Local muscle cooling or heating may affect force control independent of whole-body thermal changes. Lakie et al. (1995) tested the effects of forearm cooling and heating on pistol shooting accuracy, with hand and wrist temperature remaining thermoneutral. Interestingly, forearm cooling improved pistol shooting accuracy while forearm heating worsened accuracy, proposed to be due to the decreased and increased physiological tremor size, respectively (Lakie et al. 1994; Cooper et al. 2000). Brazaitis et al. (2012) observed decreased force variability and tremor during a 2-min maximal knee extension with lower body cooling that decreased muscle temperature but not rectal temperature, compared to passive heating of both the core and lower body. Geurts et al. (2004) studied the effects of local hand cooling on variability in force steadiness at 25 and 50% maximal voluntary contraction (MVC) abduction of the first dorsal interosseous muscle. Despite skin temperature decreasing from ~ 28 to 18 °C, the coefficient of variation (CV) remained similar. While this suggests that muscle cooling does not affect voluntary force control, the study is limited by being a relatively simple task involving maintenance of a single force level. In addition, cooling of the entire hand while testing the first dorsal interosseous muscle means that the observed changes could be confounded by reduced proprioceptive feedback (Morton and Provins 1960). Additionally, Dewhurst et al. (2007) found that cooling and heating the tibialis anterior did not affect CV between 5 and 15% MVC in a young population. Even though they did not observe differences in CV, motor unit firing rate, or the CV of the inter-pulse interval, differences were observed in the frequency analysis of the force fluctuations.

The present study examined the effects of local forearm muscle temperature manipulations on an isometric force tracking task involving wrist flexion in a progressive upward and downward staircase protocol. The flexor carpi radials (FCR) was examined as it is a small, superficial muscle that is heavily involved with manual performance in the forearm and is often exposed to environmental conditions during occupational work or exercise. Temperature manipulations were isolated to the forearm and avoided the wrist and hand to minimize potential confound from altered proprioception (Provins and Morton 1960). We hypothesized that mild muscle heating would increase force variability, while cooling would decrease variability.

Methods

Ethical approval

This study was approved by the Bioscience Research Ethics Board of Brock University (REB #17-129) and conformed to the standards set forth by the Declaration of Helsinki. All participants were informed of the experimental protocol as well as the associated risks prior to providing verbal and written consent.

Participants

Sixteen recreationally active individuals (12 males and 4 females, mean $\pm$ SD, 25 ± 3 years, 77.2 ± 10.9 kg, 179.3 ± 11.0 cm, body mass index 23.9 ± 2.1 kg m^{-2}) participated. All participants were right-handed—as determined by a 10-item questionnaire (Peters 1998)—with no known neuromuscular, circulatory, or orthopedic disorders. Skin fold thickness over the right FCR was 5.8 ± 1.6 mm.

Experimental design

All participants completed a familiarization session where mass, height, forearm length, hand lever, proximal and distal forearm circumference, and skin fold measurements using manual calipers (Harpenden, Bay International, West Sussex, UK) were taken. Participants were familiarized with performing isometric MVCs and staircase contractions using force tracking. On a second day participants arrived for the single experimental session where they performed 5 staircase contractions under neutral-, hot-, and cold- muscle conditions.

Experimental protocol

Participants avoided strenuous exercise and caffeine 12 h prior to the single experimental session. The protocol began by having the participant lying semi-recumbent allowing their right (dominant, experimental) arm to rest comfortably on a table. The FCR muscle belly was located by manual palpations, and then the skin was shaved, abraded (Nuprep, Weaver and Company, Aurora, USA), and cleansed with isopropyl alcohol. Skin–electrode impedance was kept < 10 kΩ as measured by an impedance meter (Grass EZM5, Astro-Med Inc., West Warwick, USA). Placement of recording electrodes was determined by finding the motor point of the FCR using a repeated low-level stimulation passed over the skin's surface. Pediatric Ag/AgCl electrodes (3 mm diameter, F-E9M, GRASS Technologies) were fixed to the skin using two-sided tape and electrolyte gel (Signa Gel®, Parker

Laboratories, Fairfield, USA). Electrodes were placed in a bipolar electrode configuration with one electrode on the motor point and the second electrode immediately distal (Green et al. 2015) resulting in an inter-electrode distance of 10 mm. A self-adhesive ground electrode was placed on the dorsal hand. A thermocouple (PVC-T-24-190, Omega Environmental Inc., Laval, Canada) was positioned distal to the FCR electrodes to assess local skin temperature.

Participants placed their arm in a unit isolating isometric wrist flexion by limiting wrist deviation or the use of elbow or shoulder flexion to enhance force production. The hand was placed between two bars that were secured at the metacarpophalangeal joints. These bars were affixed to a calibrated load cell (MB-100, Interface, Scottsdale, USA). A handheld two-pronged probe with anode and cathode (inter-electrode distance of 2 cm) in series was used to stimulate the median nerve at the elbow crease. Evoked potentials were elicited (Grass S88 stimulator and SIU8T isolation unit, Astro-Med Inc.) with a 0.5-ms square-wave pulse. The stimulation level was 110% of the maximal stimulation level needed to elicit a maximal M-wave, determined as the point in which no further increase could be elicited. Twitch force was recorded from the evoked contractions to examine contractile properties. The participants then completed 3 isometric MVCs lasting 4-s with 2-min inter-trial rest. The highest baseline MVC force was used to calculate the force target levels during the staircase contractions.

The experimental forearm was then wrapped in Tygon® tubing (Fig. 1) and connected to a submersion pump with a flow rate of 2.7 L min^{-1}. In contrast to thermal manipulation using water immersion or air, this setup permitted the maintenance of local forearm temperature during the neuromuscular battery. Water temperature circulating through the tubing was maintained at ~ 13 °C (cold), ~ 33 °C (neutral), or ~ 44 °C (hot), with local skin temperature during MVC testing recorded for analysis. To verify substantive changes in limb blood flow between cold, neutral, and hot, a subset of participants ($n = 12$, 10 males, 2 females) had
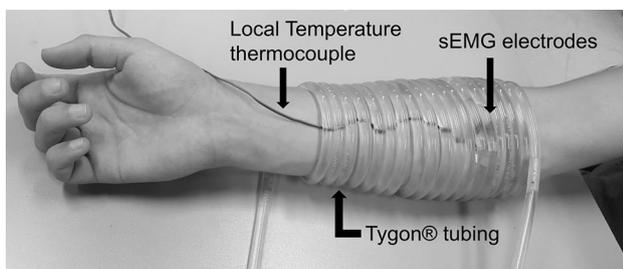
brachial artery diameter and blood flow velocity assessed using Doppler ultrasound (Vivid i, GE, USA) at the end of each temperature manipulation; all sonography and analyses were performed by the same ultrasound technician. Forearm blood flow (mL min^{-1}) was calculated as: $V_{mean} \cdot \pi(\text{vessel diameter}/2)^2 \cdot 60$.

After 10-min for the neutral water or 25-min for the cold and hot water conditions, the experimental neuromuscular battery began by evoking 3 twitches followed by a single 4-s MVC. After 2-min of rest, 5 staircase contractions were completed with 30-s inter-trial rest by tracing a force trajectory (Fig. 2a) on a monitor. The isometric contraction pattern consisted of an upwards and downwards trajectory at 10% MVC s^{-1} and maintained a 3-s plateau at each of 10, 20, 30, 20 and 10% MVC, creating a staircase trajectory. After the fifth staircase contraction, Thermal Sensation and Thermal Comfort (Gagge et al. 1967) of the experimental forearm, and Ratings of Perceived Exertion (Borg 1982) were assessed. The neutral condition always occurred first, followed by either the cold or hot conditions in a balanced order. To determine if the forearm temperature manipulations altered tactile sensitivity of the hand, 15 participants performed a two-point discrimination test at the metacarpophalangeal joint of the 2nd digit (the contact point between the hand and the brace).

Data reduction and analysis

The sEMG signals were amplified (Grass P511, Astro-Med, Inc.) to maximize the resolution of a 16-bit analogue-to-digital converter (DI-720, DATAQ Instruments, Akron, USA). The sEMG signals were band-pass filtered (3–1000 Hz) prior

Fig. 1 An image of the custom tube-lined sleeve. Each participant's forearm was wrapped in Tygon® tubing in a coil fashion from immediately distal to the elbow joint to ~ 3/4 the length of the forearm. The flow rate of the pump through the tubing was 2.7 L min^{-1} and circulated either neutral (~ 33 °C), hot (~ 44 °C), or cold (~ 13 °C) water
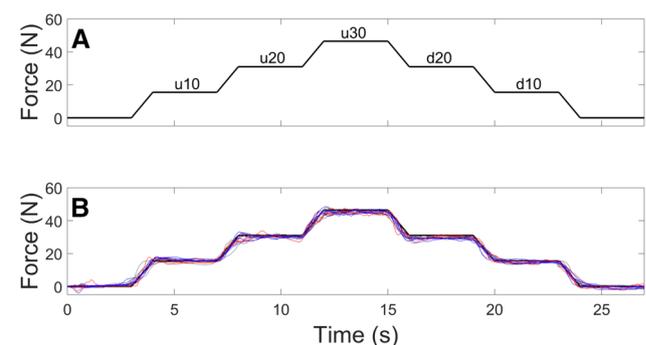

Fig. 2 Labeled staircase contractions (**a**) and representative tracings of all trials overlaid upon the template (**b**). The staircase consisted of 1-s increases and decreases to force at 10% MVC s^{-1} to 10, 20, and 30% of baseline maximal muscle force. Force plateaus at 10, 20, and 30% maximal force were 3-s long and are labeled left to right as up (u) u10, u20, u30, down (d) d20, and d10. In the representative tracing (**b**), the staircase template (black) is overlaid with the neutral (grey), hot (red), and cold (blue) trials based on this participant's 155 N baseline maximal force

to digitization at 2,000 Hz (WinDaq Acquisition, DATAQ Instruments). The force signal was sampled concurrently through the same A/D board as sEMG, then low-pass filtered at 15 Hz using a fourth-order Butterworth digital filter, offline in MATLAB® (The Mathworks Inc., Natick, USA). Peak force, rate of force development, contraction time, and half-relaxation time were calculated from the twitch force. From each MVC, average force, average temperature, root-mean-square (RMS) amplitude, and mean power frequency (MPF) was calculated from the highest, most stable 1-s portion. The following assessments were then performed on the staircase contractions to quantify performance.

Accuracy

To quantify the participants' ability to perform the staircase contractions, root-mean-square error (RMSE) was calculated for the five trials in each temperature condition by assessing the absolute difference on a point-by-point basis between the participants' actual force trace and the presented staircase template.

Reproducibility

To assess the reproducibility of the force contraction pattern, a variance ratio (Kadaba et al. 1989) was calculated for each set of 5 staircases. This consisted of interpolating the force traces to the identical number of data points, aligning the force traces in time, and comparing each trace on a point-by-point basis to determine the consistency of the muscle contraction pattern. The variance ratio provides an index of variability between trials, whereby a lower value indicates less variability; for further methodology see Green et al. (2014).

Force steadiness

To assess force steadiness, a CV was assessed from the most stable 2-s of each force plateau, as determined by taking the best 2-s CV from a moving average (25-ms increments) conducted across the 3-s plateau.

In addition, sEMG RMS amplitude and MPF were calculated from a 0.5-s window of each plateau to maximize signal stability. The same moving average procedure—but in 10-ms increments—was used to find the steadiest 0.5-s windows from which to analyze these measures.

Statistical analysis

For the staircase contractions for CV, RMS amplitude, and MPF a 3 (temperature) × 5 (force level) repeated measures analysis of variance (ANOVA) was performed. For twitch characteristics, MVCs, and where appropriate for

the staircase contractions (RMSE, variance ratio), one-way repeated measures ANOVAs were performed to compare conditions (i.e., neutral, warm, cold). Where a significant interaction effect was found, Bonferroni post hoc multiple comparisons were performed. Ordinal data (thermal sensation, thermal comfort, and RPE) was expressed as median ± interquartile range, and differences assessed with a Friedman's ANOVA. For ordinal data, Dunn's test was performed when significant interaction effects were found. All statistical analyses were performed in GraphPad Prism 7 (GraphPad Software Inc. La Jolla, USA), and statistical significance was set a $P < 0.05$. Data are presented as mean ± standard error of the mean, except for ordinal data—which is expressed as median ± interquartile range. Where the omnibus F ratio was significant, P values are representative of pairwise comparisons (i.e., all = neutral vs hot, neutral vs cold, cold vs hot).

Results

Thermal manipulation

The thermal protocol was successful in eliciting the desired local temperatures. Local forearm temperature during the MVC was 33.6 ± 0.2 °C after the neutral condition, 39.9 ± 0.2 °C after the hot manipulation, and 20.9 ± 0.4 °C after the cold treatment (all $P < 0.001$). In a subsample of 12 participants (10 M, 2 F), forearm blood flow was 123 ± 16 mL min^{-1} at baseline and increased to 264 ± 39 mL min^{-1} after heating and reduced to 68 ± 7 mL min^{-1} following cooling (all $P \leq 0.005$). Thermal sensation was 4 ± 1 at neutral, increasing to 6 ± 1 after heating ($P = 0.204$ vs neutral) and decreasing to 2 ± 1 following cooling ($P \leq 0.024$ vs both). Thermal comfort followed similar patterns, as participants perceived themselves as comfortable at neutral (1 ± 1) and hot (1 ± 1, $P > 0.999$) while cooling decreased comfort (2 ± 1, $P \leq 0.041$ vs both). The staircase contractions were perceived as more difficult during the cold (13 ± 4) compared to neutral (11 ± 3, $P = 0.041$ vs cold) but was not affected by heating (13 ± 3, $P \geq 0.086$ vs both). No difference was observed in tactile sensitivity during a 2-pt discrimination test in a pilot sample of 15 participants during neutral (0.8 ± 0.1 cm), hot (0.7 ± 0.1 cm), or cold conditions [0.7 ± 0.1 cm; $F_{(2,14)} = 0.593$, $P = 0.545$].

Contractile properties

The thermal protocol was successful in changing muscle contractile properties indicative of localized muscle temperature changes. Temperature affected twitch half-relaxation time, decreasing from 77.4 ± 2.3 ms at neutral to 67.2 ± 2.1 ms following heating ($P < 0.001$) and increasing to 100.9 ± 3.6 ms

after cooling ($P < 0.001$ vs both). Twitch rate of force development increased from 1.66 ± 0.10 N s^{-1} at neutral to 1.81 ± 0.11 N s^{-1} after heating ($P = 0.036$) and decreased to 1.36 ± 0.12 N s^{-1} after cooling ($P \leq 0.001$ vs both). Correspondingly, these changes altered contraction time from 92.4 ± 1.7 ms at neutral to 86.3 ± 2.3 ms after heating ($P = 0.002$) and increasing to 102.0 ± 2.4 ms after cooling ($P < 0.001$ vs both). The changes in the contractile properties from manipulating temperature did not result in any significant differences in peak twitch force (all $P \geq 0.225$) or M-wave peak-to-peak amplitude ($P = 0.176$).

Maximal voluntary contractions

There was a significant effect of temperature for maximal voluntary force produced ($F_{(15,2)} = 6.028$, $P = 0.010$) in the three temperature conditions. Maximal force of the single MVC performed after the neutral condition (131.6 ± 10.4 N) was not significantly different than at hot (120.4 ± 10.6 N, $P = 0.068$ vs neutral), but was higher than maximal force in the cold (114.1 ± 7.5 N, $P = 0.030$ vs neutral, $P = 0.355$ vs hot). RMS amplitude was not significantly different between neutral (369.3 ± 65.3 μV) and cold (384.3 ± 70.6 μV, $P = 0.904$ vs neutral), but decreased during heating (302.3 ± 44.7 μV, $P = 0.037$ vs neutral, $P = 0.078$ vs cold). Temperature affected MPF, decreasing in the cold (67.6 ± 4.3 Hz, $P < 0.001$ vs neutral) and increasing in the hot (111.7 ± 6.6 Hz, $P = 0.013$ vs neutral, $P < 0.001$ vs cold) compared to neutral (102.3 ± 6.4 Hz).

Staircase contractions

Staircase contraction percentages were calculated from mean maximal force at baseline (131.9 ± 11.5 N). Temperature did not affect RMSE (Fig. 3a) of the force trajectory relative to the staircase template ($F_{(2,14)} = 1.473$, $P = 0.247$) or the variance ratio (Fig. 3b, $F_{(2,15)} = 1.430$, $P = 0.373$). Note that one participant's data were corrupted for the RMSE calculation. See Fig. 4 for CV from 2-s windows during each plateau. RMS amplitude followed the level of force (Fig. 5a), with cold having greater RMS amplitudes than both neutral and hot. All temperatures had lower MPF (Fig. 5b) during the latter half of the staircase contractions, with heating and cooling resulting in higher and lower spectral frequencies than neutral, respectively. Upon visual inspection of the grouped means, no obvious trend was identified between sexes for accuracy (RMSE), reproducibility (VR), or steadiness (CV), and this may warrant future research.

Discussion

We previously showed no change in the variance ratio with local muscle cooling during a 10-s forearm flexion task at 50% MVC (Mallette et al. 2018). This was a relatively
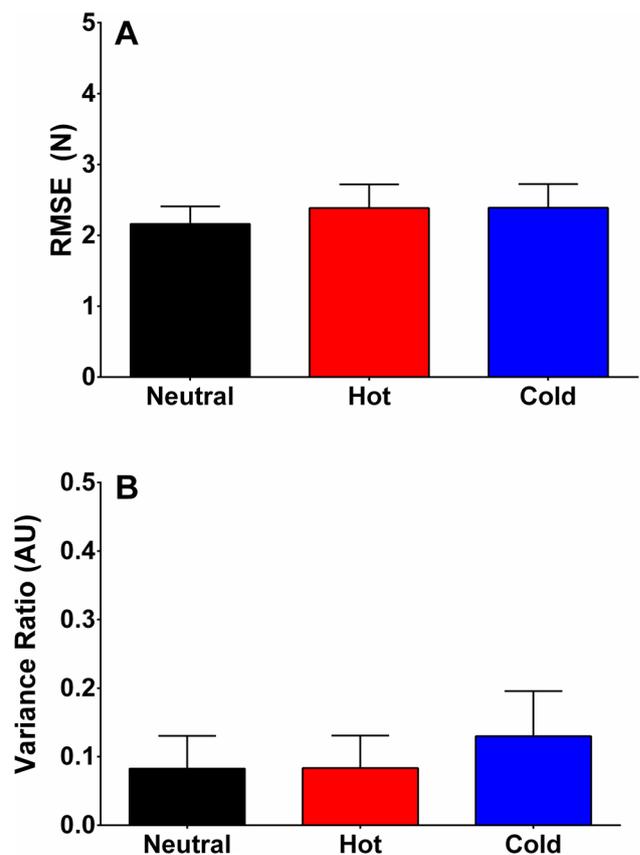

Fig. 3 Root-mean-square error (RMSE; **a**) and variance ratio (**b**) of the entire waveform for each temperature condition (red = hot; blue = cold; black = neutral)

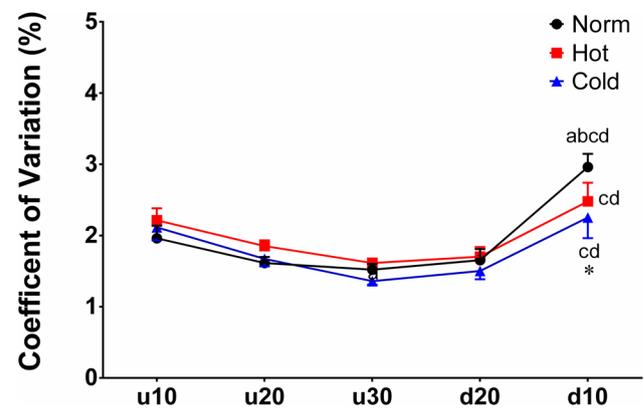**Fig. 4** Coefficient of variation during the staircase contractions for each temperature condition (red [square] = hot; blue [triangle] = cold; black [circle] = neutral). *Significantly different than neutral ($P < 0.05$). [a]Different from u10; ($P < 0.05$) [b]different from u20 ($P < 0.05$); [c]different from u30 ($P < 0.05$); [d]different from d20 ($P < 0.05$) within the same temperature condition
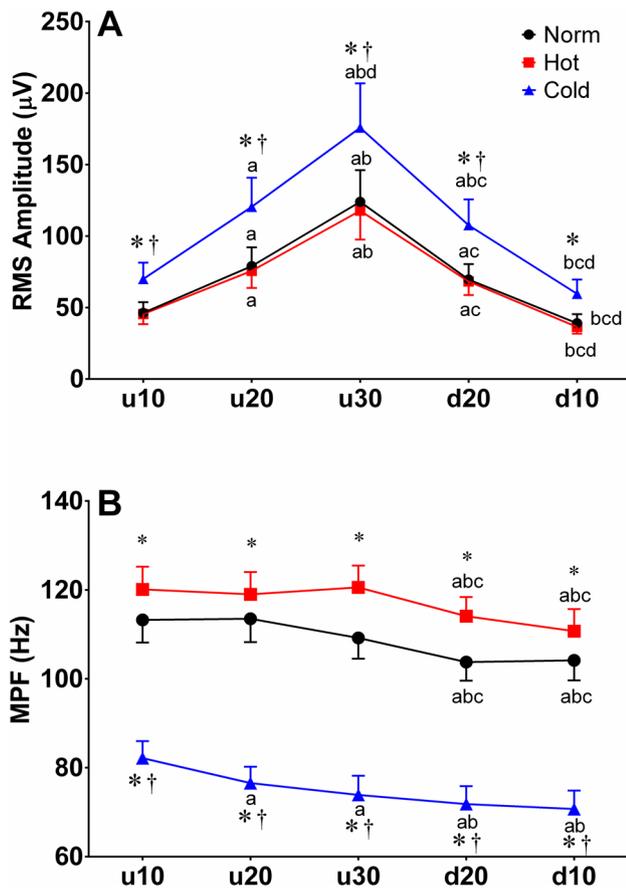
Fig. 5 Root-mean-square (RMS) amplitude (**a**) and mean power frequency (MPF; **b**) during the staircase contractions for each temperature condition (red [square] = hot; blue [triangle] = cold; black [circle] = neutral). *Significantly different than neutral ($P < 0.05$). [†]Significantly different than hot ($P < 0.05$). [a]Different from u10; ($P < 0.05$) [b]different from u20 ($P < 0.05$); [c]different from u30 ($P < 0.05$); [d]different from d20 ($P < 0.05$) within the same temperature condition

simple task, and we hypothesized that a more complex multi-plateau task would amplify the effect of temperature changes. This study thus examined the effects of local forearm muscle heating and cooling on force variability during a submaximal, isometric staircase force tracking task. Muscle temperature changes did not affect accuracy, reproducibility, or force variability during each plateau of a staircase contraction from 0 to 30% maximal force. Notably, this occurred with a protocol whereby forearm muscle temperature was altered without affecting proprioception at the wrist or contact point at the hand. Therefore, our findings suggest that the ability to perform an isometric force tracking task at submaximal forces is not affected by muscle temperature changes alone. A number of factors may have contributed to this stability.

Previous work involving local muscle temperature changes has not shown changes in force variability

during submaximal force matching tasks (Geurts et al. 2004; Dewhurst et al. 2007; Phillips et al. 2017; Mallette et al. 2018). However, these studies examined relatively simple, isometric force-matching tasks that involved only one force plateau. Alternatively, pistol shooting performance has been shown to be affected by forearm muscle temperature, with cooler temperatures being associated with greater accuracy (Lakie et al. 1995). Therefore, we hypothesized that the multi-plateaued force-matching task in the present study would be affected by local temperature alterations similar to Lakie et al. (1995). However, one interpretation of our results is that our task may not have been complex enough to demonstrate a temperature effect. Indeed, muscle temperature has been shown to play a key role in speed of movements. Forearm cooling reduces the speed of maximal rhythmic wrist flexion and extension movements from ~6 to ~1 Hz (Lakie et al. 1986). As the changes in force requirements in the current study were performed over 1-s, perhaps the force-matching requirements were too slow to see any potential impairments.

Interestingly, previous work involving lower body heating and cooling show increased and decreased CV during a 2-min maximal knee extension, respectively (Brazaitis et al. 2010, 2012). However, these results need to be interpreted carefully for two reasons. First, the passive heating condition increased both rectal and muscle temperatures, whereas the cooling condition reduced only muscle temperature, resulting in an unbalanced comparison of altered central and peripheral temperatures in one condition vs only altered peripheral temperature in the other. This can be problematic, as neural drive decreases with whole-body heating (Thomas et al. 2006; Brazaitis et al. 2010) and increase with whole-body cooling (Solianik et al. 2015; Brazaitis et al. 2016), with one study demonstrating no change (Cahill et al. 2011). Secondly, muscle cooling extends isometric muscle performance (Thornley et al. 2003), and this may have resulted in less fatigue during the 2-min MVC, thus, the decreased CV may have resulted in a less negative slope during the 2-min MVC.

The variability of motor unit firing rates can be a major factor influencing the variability of force (Moritz et al. 2005; Tracy et al. 2005). Therefore, it is possible that force variability changes during whole-body heating and cooling are due to alterations in motor unit firing variability, which would not likely be affected by local heating and cooling (Dewhurst et al. 2007). A negative relationship between voluntary activation and force variability is likely a function of lower motor unit recruitment resulting in decreased voluntary activation, and increased variability of motor unit firing rates (Hamilton et al. 2004). The present study demonstrated adaptations in neural drive with local heating and cooling, but this was limited to changes in RMS amplitude and MPF of the sEMG signal, which are likely

due to peripheral (i.e., muscle fiber conduction velocity) rather than central adaptations (Rutkove 2001; Racinais and Oksa 2010).

Although we observed no change in force variability, this could be due to the low relative force ($\leq 30\%$ MVC) used in the present study since the recruitment range of the FCR is ~ 50% of maximal force (Calancie and Bawa 1985). Indeed this pattern of no force variability changes during light contractions has been observed previously with muscle heating and cooling during a simple force task of maintaining a single force level at ~ 5 to 50% MVC (Geurts et al. 2004; Dewhurst et al. 2007; Phillips et al. 2017; Mallette et al. 2018). Additionally, our findings may be limited to isometric contractions since dynamic and iso-inertial tasks have been shown to differ from isometric tasks in motor unit recruitment thresholds (Ivanova et al. 1997), RMS amplitude (Coletta et al. 2018), and force steadiness (Hortobágyi et al. 2001). Therefore, the current findings support and extend this previous work to a multi-plateaued isometric force-matching task between 10–30% MVC.

Implementing the tube-lined sleeve that covered only the forearm without altering hand, wrist, or elbow temperatures provided several methodological strengths. Notably, it allowed us to isolate thermal manipulations to the forearm muscles, while also permitting thermal control of the forearm throughout the neuromuscular tests. Previous works that manipulated the entire limb, surrounding joints, or body temperature (Brazaitis et al. 2010; Phillips et al. 2017; Mallette et al. 2018) would change temperature of the skin contacting the force brace, which could alter proprioception (Morton and Provins 1960; Provins and Morton 1960), viscosity of the synovial fluid (Hunter et al. 1952), or motoneuron excitability via joint cooling (Hopkins and Stencil 2002). When hand or finger temperature is < 15 °C, impairments to manual dexterity and applied tasks occur (Havenith et al. 1995; Heus et al. 1995; Cheung et al. 2003) from reduced proprioception and tactile sensitivity (Morton and Provins 1960; Provins and Morton 1960). Cheung et al. (2008) observed that hand cooling resulted in an increased grip force throughout a constrained and cyclical up–down movement, likely to increase the safety margin in a compensatory fashion from less afferent feedback about how the object is being manipulated. During many previous works (Lakie et al. 1995; Geurts et al. 2004; Brazaitis et al. 2010; Mallette et al. 2018), the thermal manipulation occurred in water baths, whereby the limb was removed from the water prior to neuromuscular testing in a thermoneutral environment, thus negating some of the impact of the temperature changes over the duration of their neuromuscular batteries. The current study maintained thermal control by having the pump remain on during the force tracking task.

Methodological considerations

We used skin temperature as a surrogate measure of muscle temperature. We are aware that muscle and nerve temperature is more insulated than skin temperature and that skin temperature responds faster and to a larger magnitude than muscle temperature; however, the FCR is a superficial and thin muscle with minimal skinfold thickness over the forearm muscles (~ 6 mm) for insulation. Moreover, the thermal stimuli were applied to the forearm for 25-min prior to any neuromuscular assessment to account for the added thermal inertia of muscle and nerve temperature. Even though we did not observe changes to M-wave peak-to-peak amplitude, the expected changes to the duration, rate of force development, and half-relaxation time of the evoked twitch accompanied by large changes to forearm blood flow are evidence of muscle temperature changes. Due to the repetitive nature of this protocol (performing the staircase contraction 15 times), motor learning of the task was possible. However, all participants thoroughly practiced the staircase contraction during a familiarization session, such that skill in task performance should have stabilized. As well, even though the neutral condition always preceded the hot and cold conditions, it did not have higher variability than the following temperature conditions. Therefore, we are confident that motor learning of the task occurred during the familiarization trial and did not influence the results of the study.

Conclusions

In summary, we isolated and manipulated forearm temperature to examine the effects of altered muscle temperature on manual performance—assessed via a staircase force tracking task. 25-min of thermal manipulations via a custom tube-lined sleeve successfully changed muscle temperature evident through changes in the twitch duration, spectral frequencies, maximal voluntary force, and forearm blood flow. Muscle heating or cooling did not change the ability to perform a staircase isometric force task, assessed through RMSE and variance ratio of the entire contractions and stability during each force plateau. As hand temperature was not manipulated, it is likely that proprioception of the hand was not altered. Therefore, manual performance of a multi-plateaued isometric force task to 30% of maximal force was not altered by changing muscle temperature while the hand was exposed to a thermoneutral environment.

Compliance with ethical standards

References

Borg GA (1982) Psychophysical bases of perceived exertion. Med Sci Sports Exerc 14:377–381

Brazaitis M, Skurvydas A, Vadopalas K, Daniusevičiūtė L (2010) Force variability depends on core and muscle temperature. J Therm Biol 35:386–391. https://doi.org/10.1016/j.jtherbio.2010.08.002

Brazaitis M, Skurvydas A, Pukėnas K et al (2012) The effect of temperature on amount and structure of motor variability during 2-minute maximum voluntary contraction. Muscle Nerve 46:799–809. https://doi.org/10.1002/mus.23397

Brazaitis M, Paulauskas H, Skurvydas A et al (2016) Brief rewarming blunts hypothermia-induced alterations in sensation, motor drive and cognition. Front Physiol. https://doi.org/10.3389/fphys.2016.00592

Cahill F, Kalmar JM, Pretorius T et al (2011) Whole-body hypothermia has central and peripheral influences on elbow flexor performance. Exp Physiol 96:528–538. https://doi.org/10.1113/expphysiol.2010.054973

Calancie B, Bawa P (1985) Voluntary and reflexive recruitment of flexor carpi radialis motor units in humans. J Neurophysiol 53:1194–1200

Cheung SS, Montie DL, White MD, Behm D (2003) Changes in manual dexterity following short-term hand and forearm immersion in 10 C water. Aviat Space Environ Med 74:990–993

Cheung SS, Reynolds LF, Macdonald MAB et al (2008) Effects of local and core body temperature on grip force modulation during movement-induced load force fluctuations. Eur J Appl Physiol 103:59–69. https://doi.org/10.1007/s00421-008-0671-4

Coletta NA, Mallette MM, Gabriel DA et al (2018) Core and skin temperature influences on the surface electromyographic responses to an isometric force and position task. PLoS One 13:e0195219. https://doi.org/10.1371/journal.pone.0195219

Cooper C, Evidente VGH, Hentz JG et al (2000) The effect of temperature on hand function in patients with tremor. J Hand Ther 13:276–288

Dewhurst S, Graven-Nielsen T, De Vito G, Farina D (2007) Muscle temperature has a different effect on force fluctuations in young and older women. Clin Neurophysiol 118:762–769. https://doi.org/10.1016/j.clinph.2006.12.006

Gagge AP, Stolwijk JAJ, Hardy JD (1967) Comfort and thermal sensations and associated physiological responses at various ambient temperatures. Environ Res 1:1–20. https://doi.org/10.1016/0013-9351(67)90002-3

Geurts C, Sleivert GG, Cheung SS (2004) Temperature effects on the contractile characteristics and sub-maximal voluntary isometric force production of the first dorsal interosseus muscle. Eur J Appl Physiol 91:41–45. https://doi.org/10.1007/s00421-003-0938-8

Giesbrecht GG, Wu MP, White MD et al (1995) Isolated effects of peripheral arm and central body cooling on arm performance. Aviat Space Environ Med 66:968–975

Green LA, Parro JJ, Gabriel DA (2014) Quantifying the familiarization period for maximal resistive exercise. Appl Physiol Nutr Metab 39:275–281. https://doi.org/10.1139/apnm-2013-0253

Green LA, McGuire J, Gabriel DA (2015) Flexor carpi radialis surface electromyography electrode placement for evoked and voluntary measures. Muscle Nerve 52:818–825. https://doi.org/10.1002/mus.24631

Hamilton AF, de C, Jones, Wolpert KE DM (2004) The scaling of motor noise with muscle strength and motor unit number in humans. Exp Brain Res 157:417–430. https://doi.org/10.1007/s00221-004-1856-7

Havenith G, Heus R, Daanen HA (1995) The hand in the cold, performance and risk. Arctic Med Res 54:37–47

Heus R, Daanen HAM, Havenith G (1995) Physiological criteria for functioning of hands in the cold: a review. Appl Ergon 26:5–13. https://doi.org/10.1016/0003-6870(94)00004-I

Hopkins JT, Stencil R (2002) Ankle cryotherapy facilitates soleus function. J Orthop Sports Phys Ther 32:622–627

Hortobágyi T, Tunnel D, Moody J et al (2001) Low- or high-intensity strength training partially restores impaired quadriceps force accuracy and steadiness in aged adults. J Gerontol Ser A 56:B38–B47. https://doi.org/10.1093/gerona/56.1.B38

Hunter J, Kerr EH, Whillans MG (1952) The relation between joint stiffness upon exposure to cold and the characteristics of synovial fluid. Can J Med Sci 30:367–377. https://doi.org/10.1139/cjms52-047

Ivanova T, Garland SJ, Miller KJ (1997) Motor unit recruitment and discharge behavior in movements and isometric contractions. Muscle Nerve 20:867–874

Kadaba MP, Ramakrishnan HK, Wootten ME et al (1989) Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. J Orthop Res 7:849–860. https://doi.org/10.1002/jor.1100070611

Lakie M, Walsh EG, Wright GW (1986) Control and postural thixotropy of the forearm muscles: changes caused by cold. J Neurol Neurosurg Psychiatry 49:69–76. https://doi.org/10.1136/jnnp.49.1.69

Lakie M, Walsh EG, Arblaster LA et al (1994) Limb temperature and human tremors. J Neurol Neurosurg Psychiatry 57:35–42

Lakie M, Villagra F, Bowman I, Wilby R (1995) Shooting performance is related to forearm temperature and hand tremor size. J Sports Sci 13:313–320. https://doi.org/10.1080/02640419508732245

Mallette MM, Green LA, Gabriel DA, Cheung SS (2018) The effects of local forearm muscle cooling on motor unit properties. Eur J Appl Physiol 118:401–410. https://doi.org/10.1007/s00421-017-3782-y

Moritz CT, Barry BK, Pascoe MA, Enoka RM (2005) Discharge rate variability influences the variation in force fluctuations across the working range of a hand muscle. J Neurophysiol 93:2449–2459. https://doi.org/10.1152/jn.01122.2004

Morton R, Provins KA (1960) Finger numbness after acute local exposure to cold. J Appl Physiol 15:149–154. https://doi.org/10.1152/jappl.1960.15.1.149

Peters M (1998) Description and validation of a flexible and broadly usable handedness questionnaire. Laterality Asymmetries Body Brain Cogn 3:77–96. https://doi.org/10.1080/713754291

Phillips K, Noh B, Gage M, Yoon T (2017) The effect of cold ambient temperatures on climbing-specific finger flexor performance. Eur J Sport Sci 17:885–893. https://doi.org/10.1080/17461391.2017.1328707

Provins KA, Morton R (1960) Tactile discrimination and skin temperature. J Appl Physiol 15:155–160. https://doi.org/10.1152/jappl.1960.15.1.155

Racinais S, Oksa J (2010) Temperature and neuromuscular function. Scand J Med Sci Sports 20:1–18

Rutkove SB (2001) Effects of temperature on neuromuscular electrophysiology. Muscle Nerve 24:867–882. https://doi.org/10.1002/mus.1084

Solianik R, Skurvydas A, Pukėnas K, Brazaitis M (2015) Comparison of the effects of whole-body cooling during fatiguing exercise in males and females. Cryobiology 71:112–118. https://doi.org/10.1016/j.cryobiol.2015.04.012

Thomas MM, Cheung SS, Elder GC, Sleivert GG (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

Thornley LJ, Maxwell NS, Cheung SS (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

Tracy BL, Maluf KS, Stephenson JL et al (2005) Variability of motor unit discharge and force fluctuations across a range of muscle forces in older adults. Muscle Nerve 32:533–540. https://doi.org/10.1002/mus.20392