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Original Research

The effect of local skin cooling before a sustained, submaximal isometric contraction on fatigue and isometric quadriceps femoris performance: A randomized controlled trial☆

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ABSTRACT

The central- and peripheral mechanisms by which heat strain limits physical performance are not fully elucidated. Nevertheless, pre-cooling is often used in an attempt to improve subsequent performance. This study compared the effects of pre-cooling vs. a pre-thermoneutral application on central- and peripheral fatigue during 60% of isometric maximum voluntary contraction (MVC) of the right quadriceps femoris muscle. Furthermore, the effects between a pre-cooling and a pre-thermoneutral application on isometric MVC of the right quadriceps femoris muscle and subjective ratings of perceived exertion (RPE) were investigated. In this randomized controlled trial, 18 healthy adults voluntarily participated. The participants received either a cold (experimental) application (+8 °C) or a thermoneutral (control) application (+32 °C) for 20 min on their right thigh (one cuff). After the application, central (fractal dimension – FD) and peripheral (muscle fiber conduction velocity – CV) fatigue was estimated using sEMG parameters during 60% of isometric MVC. Surface EMG signals were detected from the vastus medialis and lateralis using bidimensional arrays. Immediately after the submaximal contraction, isometric MVC and RPE were assessed. Participants receiving the cold application were able to maintain a 60% isometric MVC significantly longer when compared to the thermoneutral group (mean time: 78 vs. 46 s; p=0.04). The thermoneutral application had no significant impact on central fatigue (p > 0.05) compared to the cold application (p=0.03). However, signs of peripheral fatigue were significantly higher in the cold group compared to the thermoneutral group (p=0.008). Pre-cooling had no effect on isometric MVC of the right quadriceps muscle and ratings of perceived exertion. Pre-cooling attenuated central fatigue and led to significantly longer submaximal contraction times compared to the pre-thermoneutral application. These findings support the use of pre-cooling procedures prior to submaximal exercises of the quadriceps muscle compared to pre-thermoneutral applications.

1. Introduction

Pre-cooling strategies are frequently used for the purpose of reducing body temperature prior to exercise, decreasing heat strain and improving performance (Cotter et al., 2001; Duffield et al., 2010). A recently published meta-analytical review showed that the positive effects of pre-cooling could be most beneficial before endurance exercises (Wegmann et al., 2012). In a heat-gaining environment, whole-body pre-cooling methods can be used to combat the debilitating effects of heat-stress-induced fatigue in order to increase heat storage capacity and improve exercise tolerance (Ross et al., 2013). High environmental heat stress may lead to several exertional heat-related illness types (Nichols, 2014). The most serious form is exertional heat stroke, characterized by a core temperature > 40 °C and is associated with central nervous system disturbance, hot skin and sweating (Howe and Boden, 2007). It has been demonstrated that exhaustion and high ratings of perceived exertion (RPE) are reached at muscle temperatures of 40 °C (Gonzalez-Alonso et al., 1999). Hyperthermia-induced fatigue

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during prolonged exercise is mainly due to perturbations in the brain's ability to sustain sufficient activation of the skeletal muscles. It has been assumed that the elevated brain temperature itself, which increases parallel with that of the body core, is the main factor affecting motor activation, but feedback from the skeletal muscles and activity of the dopaminergic system also seem to be important (Nybo, 2008, 2012). However, the absence of irreversible damage to the human brain during and after hyperthermia may indicate that these mechanisms have not yet been clearly understood (Robertson and Marino, 2017). It has also been shown that lower ambient heat stress and auxiliary cooling of the skin improves endurance exercise performance (Gonzales et al., 2014; Uckert and Joch, 2007). However, excessive external cooling strategies have been shown to reduce muscular performance as a result of reductions in muscle/nerve conduction velocity (Ranalli et al., 2010).

It has been demonstrated that exhaustive exercises do not only cause peripheral but also central fatigue, leading to decreased muscle contractility (Bigland-Ritchie et al., 1978). Two main physiological factors can explain the different myoelectric manifestations of peripheral- and central fatigue: (1) the slowing of motor-unit action potentials due to reduced conduction velocity and (2) the synchronization of motor-units by the central nervous system to increase the mechanical output when the whole motor-unit pool is recruited (Merletti and Parker, 2004).

During submaximal and sustained maximum voluntary contraction (MVC), healthy subjects developed both central- and peripheral fatigue, leading to reduced performance output (Schillings et al., 2003). Numerous researchers, with conflicting results, have investigated the effects of local thigh water-perfused or ice-cuff cooling on strength parameters, such as isometric muscle contractions of the quadriceps femoris muscles (Cotter et al., 2001; Pointon et al., 2011). One study investigated the effects of a 20 min cold application (10 °C water temperature) on isometric MVC of the lower leg and found that isometric force was reduced in the tibialis anterior muscle (Halder et al., 2014). Another study showed that local ice bag cooling (approximately 20–35 min) led to significant lower MVC values of the quadriceps muscle in young (mean ± SD age: 22 ± 2 years) individuals (Dewhurst et al., 2010). However, the largest efficacy for pre-cooling strategies can be observed for endurance tasks, whereas the effects on short active muscle contractions is considerably smaller (Wegmann et al., 2012). It has been demonstrated that a 20-min local ice-pack application leads to significantly higher peak power output during a 40-min intermittent cycle sprint performance when compared to non-cooling techniques (Castle et al., 2006). The use of cold water immersions is becoming very popular as a standard technique for lowering tissue temperature (McDermott et al., 2009). However, the practical execution of such cold water immersions is not possible everywhere (water access, cooling a full team) (Marino, 2002; Minett et al., 2011). Moreover, results that question the effects of cooling have been reported. A recently published study showed that cooling can have a negative impact on strength training adaptions in well trained students (Frohlich et al., 2014). It has also been demonstrated that pre-cooling can have a detrimental effect on short active muscle contractions (Schniepp et al., 2002). Studies using local cooling devices for investigating thermal effects on submaximal MVC and central vs. peripheral fatigue are limited.

It has been suggested that central- and peripheral fatigue are related to changes in fractal dimension (FD) and muscle fiber conduction velocity (CV) during submaximal isometric contractions (Mesin et al., 2009). One study suggested that FD analyses can be used as an indicator for central fatigue mechanisms with respect to CV in fatiguing contractions (Boccia et al., 2016). Another study evaluated FD and CV slopes as indexes of central- and peripheral fatigue during isometric contractions in humans (Beretta-Piccoli et al., 2015). The authors of this study pointed out that further studies are needed to investigate FD and CV as indexes of central- and peripheral fatigue. There is, to our knowledge, no published study that has investigated the effect of pre-cooling on central- and peripheral fatigue using these parameters. Athletes, patients and researchers might profit from these further investigations.

Therefore, the aim of this randomized controlled trial was to compare the effects of a single pre-cooling application vs. a pre-thermoneutral application on both central- and peripheral fatigue, using FD and CV, during a 60% of isometric MVC contraction of the right quadriceps femoris muscle till exhaustion. Furthermore, the effects between pre-cooling and a pre-thermoneutral application after the exhaustive 60% of isometric MVC task on isometric MVC of the right quadriceps femoris muscle and RPE were investigated. We hypothesized that local skin pre-cooling would have a positive effect on peripheral fatigue and lead to longer submaximal contraction times but not on isometric MVC after the exhaustive exercise when compared to a pre-thermoneutral application. To our knowledge, this is the first study that compares these parameters in this specific experimental set-up.

2. Methods

2.1. Design and participants

In this randomized controlled trial, 18 young, healthy adults (11 female and 7 male), regularly involved in moderate physical endurance activity voluntarily participated in this study. Four female and 5 male participants were randomly assigned to the cold group (experimental) and the remaining 9 (7 females and 2 males) were assigned to the thermoneutral (control) group. Randomization was ensured by drawing lots. Mixed gender population has already been used in the field of cryotherapy studies (Costello et al., 2012; Crowe et al., 2007). The participants completed a pre-test questionnaire and were excluded if they had a history of lower limb injuries in the past twelve months, current pain symptoms, cardiovascular diseases or any contraindication for cryotherapy including Raynaud's disease or if they were not between the age of 18 and 30 years. The participants were fully informed about the risks and discomforts before signing an informed-consent form. The Swiss ethical committee of Zurich (KEK-ZH.Nr. 2015-0113) approved this study in accordance with the declaration of Helsinki (ICH-GCP). The participants had to appear in a healthy and in a fully recovered state at the beginning of the study – without any symptoms of exhaustion (rated on a 6–20 BORG scale). Finally, participants were instructed to refrain from alcohol and other beverages that might influence the results such as caffeinated soft drinks, coffee and isotonic drinks at least 24 h prior to the start of the experiment.

2.2. Baseline measurements

After randomization, the participants' anthropometric data were collected. Standing body height was measured to the nearest 0.1 cm, using a GPM stadiometer (Zurich, Switzerland). Body weight and estimated lower body fat percentage were measured using the athlete modus of the TANITA-TBF 611 scale (Tokyo, Japan). The isometric MVC of the right quadriceps femoris muscle was determined using a custom-made (Cor 1-V1.0) ergometer chair for biomechanical measurements (OT Bioelettronica, Torino, Italy). The maximum force of the knee extensors was determined with a force meter operating linearly in the range of 0–1000 N. The signal was amplified with the MISO II (OT Bioelettronica, Torino, Italy). The participants' force was displayed on a monitor, providing real-time feedback. All measurements on the ergometer chair were conducted in a seated position and at a knee angle of 120° and a hip angle of 100° as previously conducted (Beretta-Piccoli et al., 2015). The participants' right leg was attached to the ergometer chair with a strap above the right malleoli lateralis and medialis, ensuring an isometric maximum performance. The participant was then strapped in to the ergometer chair with a seatbelt (Sparco, Irvine, USA). The isometric MVC of the right quadriceps femoris muscle was measured three times in a row with a two-minute break between the bouts. The best of the three trials was used for the analyses and to estimate the individual 60% of isometric MVC value. RPE was measured in standing position on a 6–20 BORG scale (Borg, 1982). After the baseline measurements, the participants received the thermotherapy.

2.3. Thermotherapy

The thermotherapy was applied using the medical device Zamar® Therapy-ZT Clinic from Zamar® medical (Porec, Croatia, www.zamarmedical.com). To compare the effects of pre-cooling vs. a pre-thermoneutral application, participants received either the experimental temperature (cold: +8 °C) or the thermoneutral (control) temperature (+32 °C) both over the duration of 20 min. It has been demonstrated in a recently published review that water temperatures of approximately 35 °C (range: 24–36 °C) are considered to be thermoneutral (Versey et al., 2013). A thigh cuff (Zamar® Medical) was placed directly onto the skin and wrapped around the right thigh with a minimum level of pressure to avoid any compression effects. The Zamar® Therapy-ZT Clinic device applied a constant temperature around the whole area under the cuff during the entire application time. The Zamar Therapy® device creates a constant temperature by circulating a lubrication mixture (consisting of propylene glycol and demineralized water) between the unit and the sleeve via hoses. To minimize bias the participants were not allowed to inform any researcher about their perceived thermal sensation during the whole experiment.

2.4. Central- and peripheral fatigue measurements during 60% of isometric MVC

After the thermotherapy, the participants immediately had to maintain an isometric contraction at 60% of their individual isometric MVC as long as possible until the force value decreased below 90% of the 60% target. Participants were able to follow their performance as the individual 60% isometric MVC mark and the corresponding 90% mark were displayed on a monitor. Time to exhaustion during this test was automatically measured and used as the submaximal contraction time. Central- and peripheral fatigue was measured on the ergometer chair during this procedure under the same conditions as described above. The myoelectrical signals were detected from the vastus medialis (VM) and vastus lateralis (VL) from semidisposable, bidimensional arrays of 16 electrodes (3 mm diameter, 2×8 grid, 10 mm interelectrode distance, OT Bioelettronica, Torino, Italy). The electrodes were placed in order to obtain good quality sEMG signals, as previously reported (Barbero et al., 2012). These electrodes were separated from the skin by a single-use biadhesive foam layer, filled with conductive paste to reduce the possibility of occurrence of motion artefacts. The sEMG signals were amplified (EMG-USB2, OT Bioelettronica, Torino, Italy), band-pass filtered (10–750 Hz) and sampled at 2048 Hz.

2.5. Description of central- and peripheral fatigue measurements

Published results show that central- and peripheral fatigue can be described as changes in fractal dimension (FD) and muscle fiber conduction velocity (CV) detected by surface electromyography (sEMG) signals (Beretta-Piccoli et al., 2015; Bilodeau et al., 1994; Mesin et al., 2009).

It has been demonstrated that EMG measurements (estimation of the muscle fiber CV) during a submaximal voluntary contraction of the quadriceps is a reliable method for the assessment of peripheral fatigue change (Bilodeau et al., 1994; Dedering et al., 2000; Kollmitzer et al., 1999). Peripheral fatigue comprises biochemical changes within the metabolic milieu of the working muscle (e.g. impaired calcium release from the sarcoplasmic reticulum) leading to an attenuated response of neural excitation and decreased muscle fiber CV (Allen et al., 2008; Amann, 2011).

Researchers have pointed out that FD is sensitive to central fatigue but not to peripheral fatigue (Mesin et al., 2009). These researchers suggested that, beside the initial use to characterize levels of muscle activation and patterns of motor-unit recruitment (Anmuth et al., 1994; Xu et al., 1997), FD is related to motor-unit synchronization during muscle fatigue (Mesin et al., 2009). It can be considered that a decrease in FD may be an indicator of progressive motor-unit synchronization, indicating central fatigue. Significant correlations between FD and CV at 60% of isometric maximum voluntary contraction (MVC) of the quadriceps muscle suggest that a mutual interaction between central- and peripheral fatigue can arise during submaximal isometric contractions (Beretta-Piccoli et al., 2015).

2.5.1. Signal processing

The sEMG signals were visually inspected in order to select the best channels to use for variable estimations. CV of sEMG signals was computed off-line with numerical algorithms using non-overlapping signal epochs of 1 s (Mesin et al., 2009). CV values outside the physiological range (2–8 m/s) were excluded from the analysis.

FD was computed using a numerical algorithm with non-overlapping signal epochs of 1 s, as previously reported (Mesin et al., 2009). Linear regressions were used to calculate the initial value and the rate of change (calculated as the percentage ratio between the change of EMG estimate in one second and the initial value, expressed as %/s) of the EMG variables.

2.6. Follow-up measurements

Immediately after performing 60% of isometric MVC, the follow-up measurements (post-exhaustion) were performed. These measurements included the assessment of isometric MVC (of the right quadriceps muscle, three repetitions with a two minute break between the bouts) and the subjective RPE parameter. Measurements were conducted under the same conditions as described in the Section 2.2. The experimental study protocol can be seen in Fig. 1.

2.7. Statistical analysis

Data analyses were carried out using the Statistical Package for

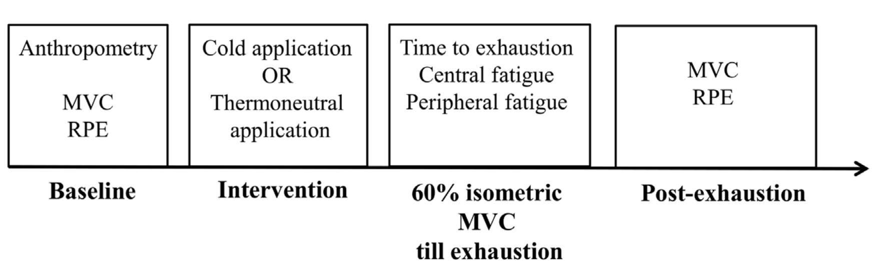

Fig. 1. Schematic representation of the test protocol. MVC=maximum voluntary contraction, RPE=ratings of perceived exertion.

Social Sciences for Windows (SPSS) version 23.0. The Test of normality, using the Shapiro-Wilk test for small sample sizes, was conducted. A two-way repeated measures ANOVA (mixed design) was used to assess time effects (for FD, CV, MVC and RPE) and time x group (cold vs. thermoneutral) interactions. In case of significant time x group interactions, one-way repeated measures ANOVAs were used to analyse the differences within-groups (pre-cold vs. post-cold and pre-thermoneutral vs. post-thermoneutral for FD, CV, MVC and RPE). Mean differences (between groups) were assessed using independent samples *t*-tests. In case of not normally distributed data the Wilcoxon rank test was performed for within-group differences or the Mann-Whitney-*U* test for between-group differences or. The negative slopes of the VM were analysed together with the negative slopes of the VL in the cold and the thermoneutral group. Effect sizes are expressed as Cohen's d values of 0.2–0.49, 0.5–0.79 and over 0.8, which were considered small, medium and large (Cohen, 1992). For the ANOVA measurements, effect sizes are expressed as partial eta squared ($\eta^2_{partial}$) values of 0.1–0.29, 0.3–0.49 and over 0.5, which were considered small, medium and large, respectively (Cohen, 1992). The level of significance was set at $p < 0.05$.

3. Results

3.1. Participants

The Shapiro-Wilk test revealed that all anthropometric data were normally distributed between the groups. There were no statistically significant differences between cold and the thermoneutral group for age (p=0.17), height (p=0.79), weight (p=0.20) and estimated lower body fat percentage (p=0.11). The anthropometric characteristics of the participants can be observed in Table 1. The authors of this study declare no conflict of interest of the participants.

3.2. Effects of pre-cooling vs. pre-thermoneutral application on central- and peripheral fatigue

The participants in the cold group were able to maintain their individual 60% of isometric MVC 32 s longer compared to the thermoneutral group. These results were significantly different between the groups, showing large effect sizes (cold: mean ± SD=77.73 ± 31.35 s, thermoneutral: mean ± SD=46.35 ± 26.79 s); t(15)=2.21, p=0.04, d=1.07 (Fig. 2a).

A small but significant time×group interaction was observed for FD ($F_{1,32}$=5.16, p=0.03, $\eta^2_{partial}$=0.13). Repeated measures analyses indicate a significantly higher decrease over time for the thermoneutral ($F_{1,17}$=33.61, $p < 0.01$) application when compared to the cold ($F_{1,15}$=24,96, $p < 0.01$) application. The initial values of FD were not significantly different between the cold (mean ± SD=1.60 ± 0.85) and the thermoneutral (mean ± SD=1.55 ± 0.02) groups; t(33)=1.97; p=0.57, d=0.08. The negative slope (%/s) of the FD during 60% of isometric MVC was significantly higher in the thermoneutral (mean ± SD=−0.07 ± 0.05) groups compared to the cold (mean ± SD=−0.03 ± 0.02) group with a large effect size; *U*=91.0, Z=−1.82, p=0.03, d=1.05 (Fig. 2b). The end values of FD were significantly lower in the thermoneutral (mean ± SD=1.55 ± 0.02) group compared to the cold (mean ± SD=1.60 ± 0.08) group showing a large effect size; t(32)=2.40, p=0.01, d=0.85.

The analyses for CV revealed no significant time x group interaction ($F_{1,21}$=2.34, p=0.14, $\eta^2_{partial}$=0.10), only a significant negative time effect ($p < 0.01$) could be observed. The initial values of CV were also not significantly different between the cold (mean ± SD=5.26 ± 0.37) and the thermoneutral (mean ± SD=5.00 ± 0.63) groups; t(27)=1.41, p=0.16, d=0.50. The decrease in CV (%/s) was significantly higher in the cold (mean ± SD=−0.19 ± 0.12) group during the 60% of isometric MVC performance, compared to the thermoneutral (mean ± SD=−0.05 ± 0.11) group with large effect sizes; t(26)=−2.88, p=0.008, d=1.21 (Fig. 2c). The end values of CV between cold (mean ± SD=1.55 ± 0.01) and thermoneutral (mean ± SD=1.55 ± 0.01) were not significantly different between the groups; t(22)=0.37, p=0.71, d=0.00.

3.3. Effects of pre-cooling vs. pre-thermoneutral application on isometric MVC and RPE

No significant time x group interaction ($F_{1,16}$=3.21, p=0.09, $\eta^2_{partial}$=0.16) or time effect ($F_{1,16}$=0.72, p=0.40, $\eta^2_{partial}$=0.04) could be observed for MVC. The baseline measurements for isometric MVC demonstrated that the cold (mean ± SD=540.75 ± 150.19 N) group and the thermoneutral (mean ± SD=430.14 ± 150.39 N) group were not significantly different at the beginning of the experiment; t(16)=1.61, p=0.12, d=0.75.

Also after normalizing isometric MVC values to 100% of the baseline values, no significant time x group interaction ($F_{1,16}$=1.82, p=0.19, $\eta^2_{partial}$=0.10) or time effect ($F_{1,16}$=0.11, p=0.73, $\eta^2_{partial}$=0.007) could be observed (Fig. 3a).

No time x group interaction ($F_{1,16}$=3.62, p=0.07, $\eta^2_{partial}$=0.18) with a significant positive time effect ($F_{1,16}$=8.53, p=0.01, $\eta^2_{partial}$=0.34) could be observed for RPE. The subjective RPE ratings showed no significant difference before (t(16)=−1.66, p=0.11, d=0.78) and after (t(16)=0.28, p=0.77, d=0.13) performing 60% of isometric MVC between the groups (Fig. 3b).

4. Discussion

The present study investigated the effects of a single pre-cooling application on both central- and peripheral fatigue, MVC and subjective RPE. The results indicate that pre-cooling delayed central fatigue mechanisms. The effect of pre-cooling on peripheral fatigue is questionable. However, the participants in the cold group were able to contract their quadriceps muscle significantly longer at 60% of isometric MVC compared to the participants in the thermoneutral group. Pre-cooling had no effect on MVC and RPE in this experimental set-up.

4.1. Effect of pre-cooling on fatigue

It has been documented that cold applications, such as ice packs and cold water immersions significantly decrease sensory and also motor nerve CV (Herrera et al., 2010, 2011). In the latter study, the authors demonstrated that dynamic exercise (15 min walking) after pre-cooling applications, accelerated the re-functioning of both sensory- and motor CV (Herrera et al., 2011). However, in the present study, the participants had to perform an isometric contraction after pre-cooling, which might explain the non-accelerated re-functioning of CV as previously observed in other studies (Herrera et al., 2011). The decreased peripheral CV in the cold group might be partially explained by these factors.

The FD slope (%/s) was significantly higher in the thermoneutral group. Based on recently published studies, this might indicate that cooling can prevent the occurrence of the central fatigue mechanism; however, these mechanisms have not been fully corroborated. A

Table 1
Anthropometric data of the participants.

	Total (n=18)	Cold (n=9)	Thermoneutral (n=9)
Age (years)	22.6 ± 1.9	23.3 ± 2.1	22.0 ± 1.6
Height (cm)	170.6 ± 10.4	174.9 ± 10.0	166.3 ± 9.4
Weight (kg)	64.8 ± 10.8	68.1 ± 11.1	61.5 ± 10.2
ELBF %	25.3 ± 8.0	22.3 ± 8.0	28.3 ± 7.2

Values are means ± SD; ELBF %=estimated lower body fat percentage.

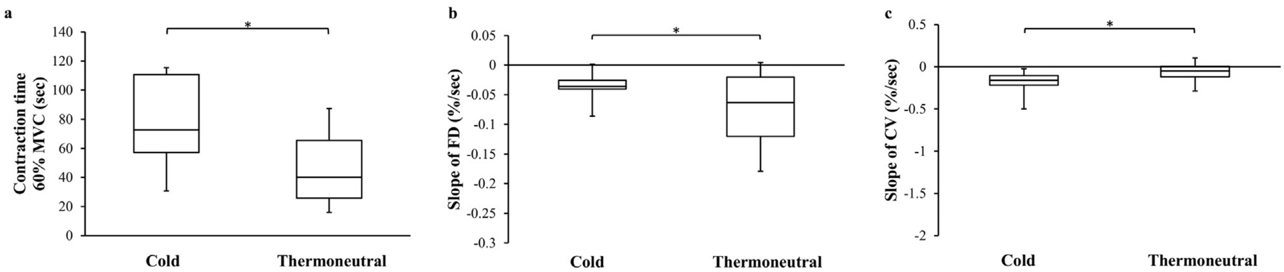

Fig. 2. Box plot of measurements during 60% of isometric MVC. 2a: Contraction time until exhaustion during 60% of isometric MVC. 2b: Decreased slope (%/s) of FD during 60% of isometric MVC. 3b: Decreased slope (%/s) of CV during 60% of isometric MVC. *P < 0.05 between groups.

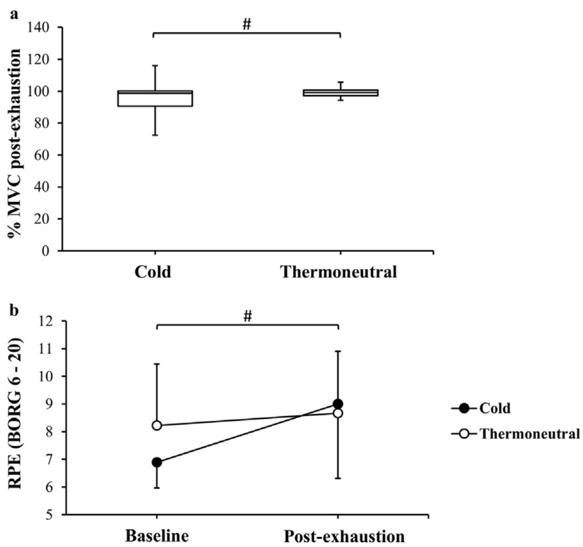

Fig. 3. Measurements in function of time for maximum voluntary isometric contraction (MVC) and subjective rated perceived exertion (RPE) for the cold and thermoneutral group. Fig. 3a: Box plot of isometric MVC presented as percent change with respect to their initial values. Fig. 3b: RPE values are presented as means ± SD. #P > 0.05 between groups.

specific definition of central fatigue is elusive. It has been postulated that central fatigue might be mediated by afferent feedback from the muscle itself or a reduction in corticospinal impulses reaching the motor neurons. The afferent feedback from the muscle itself may be the result of changes in muscle metabolites during exercise and an attempt to produce the most safe and efficient level of muscle activation (Davis and Bailey, 1997). Published data from studies using partial muscle afferent blockades in the exercising human, investigated group III/IV muscle afferent feedback. The feedback not only registers changes in the metabolic milieu of the muscle relaying it to the central nervous system, but also the influence of motor units firing at the spinal and supraspinal level (Almeida et al., 2004; Martin et al., 2008). These afferent fibers diminish the central motor drive during intense exercise to prevent a critical threshold of peripheral fatigue (Amann et al., 2009; Gagnon et al., 2012). In the present study, the thermoneutral group showed significantly higher signs of central fatigue with significantly shorter submaximal endurance contraction times compared to the cold group. This might indicate that there is a relationship between central fatigue and submaximal contraction times.

It has been demonstrated that ice packs, ice massages and cold water immersions are effective in reducing skin temperature and changing motor and sensory conduction velocity, with larger effects on the sensory nerve (Herrera et al., 2010). In the above mentioned study, the authors showed that a 15 min long cold pack application decreased mean skin temperature to around 7 °C leading to increased latency of the sural and tibial motor nerves. In another study, an ice pack application lasting 20 min, decreased skin temperature of the ankle to around 15 °C (Palmieri et al., 2006). Cold water immersions were shown to reduce mean skin temperature sufficiently (around 13 °C) leading to a change of sensory CV of the sural nerve (Herrera et al., 2010).

In our study, the peripheral fatigue in the thermoneutral group was significantly lower compared to the cold group. It can be hypothesized that the decreased peripheral muscle fiber CV in the thermoneutral group did not significantly affect the conduction of the sensory nerve, allowing sufficient afferent feedback to the central nervous system. This resulted in significantly more symptoms of central fatigue when compared to the cold group. Furthermore, the reduced muscle fiber CV in the cooled muscles is a reflection of the temperature dependency of one or more of the underlying processes, including a decreased rate of calcium release and/or slowing of the net cross-bridge attachment rate, calcium removal from the myoplasm, calcium dissociation from troponin, and cross-bridge detachment rate (de Ruiter et al., 1999). Conversely, the occurrence of higher signs of peripheral fatigue in the cold group had no negative influence on endurance contraction times. The thermoneutral group showed smaller signs of peripheral fatigue but also had significantly shorter submaximal endurance contraction times compared to the cold group (32 s). This might indicate that there is only a limited relationship between peripheral fatigue and submaximal contraction times. However, these results should be viewed with caution because the significant time effect (for CV) was not group dependent.

4.2. Effect of pre-cooling on MVC and RPE

Pre-cooling did not affect isometric MVC immediately after the 60% of isometric MVC task. This result is in line with earlier studies, showing that the effectiveness of pre-cooling is also dependent on the exercise tasks (Wegmann et al., 2012). The largest effects of pre-cooling can be expected in hot environmental conditions and for endurance exercises (Booth et al., 1997; Tyler et al., 2015; Wegmann et al., 2012). Other studies have demonstrated that isometric force production starts to reduce due to peripheral muscle cooling at any temperature below 25 °C (Davies et al., 1982; de Ruiter et al., 1999). An ice bag application of 15 min duration was not able to reduce the temperature of the triceps surae muscle below 30 °C either immediately following, or 10 min after the application (Bender et al., 2005). Therefore, it can be speculated that the muscles in the present study were either not cold enough or sufficiently warmed-up with the endurance exercise. This might explain the non-affected MVC values. Furthermore, it has been suggested that pre-cooling can only have a meaningful impact on performance if the thermal stress is large enough (long exercise durations and high ambient temperatures) (Duffield and Marino, 2007). In the present study, the participants had to perform 60% of their individual isometric MVC until exhaustion under comfortable ambient temperatures. This task and the laboratory conditions were insufficient to induce enough thermal stress. Similar findings can be observed when looking at the RPE results. No significant differences between the groups were detected post-exhaustion. Furthermore, it has to be mentioned that highly trained endurance-athletes might benefit more from pre-cooling effects (Wegmann et al., 2012). Pre-cooling seems to have no effect on maximum strength parameters such as isometric MVC under comfortable ambient temperatures after a submaximal exhaustion task.

A limitation of the present study is that no skin or muscle temperatures were assessed. Such temperature measurements may have provided useful information for the interpretation of the data. Another limitation is that we used a mixed gender population. Although the female and male participants had similar anthropometric profiles, additional skinfold measurements would have been useful owing to the effect of the amount of local adipose tissue on the decrease of tissue temperature (Jutte et al., 2001). It has been demonstrated that females predominantly accumulate more subcutaneous fat in comparison to males which in turn might have influenced the effect in the pre-cooling group (Kotani et al., 1994). Furthermore, it has been demonstrated that muscle fatigue is task specific and that women are less fatigable than men during isometric sustained contractions of the knee extensors (Hunter, 2014). Finally, FD is a relatively novel method for assessing central fatigue and further studies are needed to demonstrate its validity and reliability. The results of the present study might be of particular interest for coaches and athletes, in which submaximal muscle contractions of the quadriceps femoris muscle is an essential component of athletic performance. It can be speculated that longer contraction times and reduced central fatigue might improve performance. Local cooling, as practiced in this study, is easy to apply and easily accessible. Most likely the effect of pre-cooling is greater for submaximal contractions or endurance tasks than for maximum contractions. The results of this strict experimental set-up cannot be transferred 1:1 to a field situation as only two of the lower extremity muscles were investigated. Practically oriented studies should investigate these effects under real field conditions.

5. Conclusion

Pre-cooling attenuated central fatigue and led to significantly longer submaximal contraction times compared to the pre-thermoneutral application. The thermoneutral group had significantly higher signs of central fatigue at the end of the submaximal contraction task. Pre-cooling had no superior effect on isometric MVC and RPE compared to the pre-thermoneutral application in this experimental set-up. The results of the present study indicate that decreased muscle fiber CV do not limit endurance capacity, measured in terms of “contraction time during 60% of isometric MVC”. The decrease of contraction time in these exercises seems to be more affected by central mechanisms.

Conflict of interest

The authors declare that they have no conflict of interest.

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References

Allen, D.G., Lamb, G.D., Westerblad, H., 2008. Skeletal muscle fatigue: cellular mechanisms. Physiol. Rev. 88, 287–332.

Almeida, T.F., Roizenblatt, S., Tufik, S., 2004. Afferent pain pathways: a neuroanatomical review. Brain Res. 1000, 40–56.

Amann, M., 2011. Central and peripheral fatigue: interaction during cycling exercise in humans. Med. Sci. Sports Exerc. 43, 2039–2045.

Amann, M., Proctor, L.T., Sebranek, J.J., Pegelow, D.F., Dempsey, J.A., 2009. Opioid-mediated muscle afferents inhibit central motor drive and limit peripheral muscle fatigue development in humans. J. Physiol. 587, 271–283.

Anmuth, C.J., Goldberg, G., Mayer, N.H., 1994. Fractal dimension of electromyographic signals recorded with surface electrodes during isometric contractions is linearly correlated with muscle activation. Muscle Nerve 17, 953–954.

Barbero, M., Merletti, R., Rainoldi, A., 2012. Atlas of Muscle Inntervation Zones: Understanding Surface Electromyography and its Application.

Bender, A.L., Kramer, E.E., Brucker, J.B., Demchak, T.J., Cordova, M.L., Stone, M.B., 2005. Local ice-bag application and triceps surae muscle temperature during treadmill walking. J. Athl. Train. 40, 271–275.

Beretta-Piccoli, M., D'Antona, G., Barbero, M., Fisher, B., Dieli-Conwright, C.M., Clijsen, R., Cescon, C., 2015. Evaluation of central and peripheral fatigue in the quadriceps using fractal dimension and conduction velocity in young females. PLoS One 10, e0123921.

Bigland-Ritchie, B., Jones, D.A., Hosking, G.P., Edwards, R.H., 1978. Central and peripheral fatigue in sustained maximum voluntary contractions of human quadriceps muscle. Clin. Sci. Mol. Med. 54, 609–614.

Bilodeau, M., Arsenault, A.B., Gravel, D., Bourbonnais, D., 1994. EMG power spectrum of elbow extensors: a reliability study. Electromyogr. Clin. Neurophysiol. 34, 149–158.

Boccia, G., Dardanello, D., Beretta-Piccoli, M., Cescon, C., Coratella, G., Rinaldo, N., Barbero, M., Lanza, M., Schena, F., Rainoldi, A., 2016. Muscle fiber conduction velocity and fractal dimension of EMG during fatiguing contraction of young and elderly active men. Physiol. Meas. 37, 162–174.

Booth, J., Marino, F., Ward, J.J., 1997. Improved running performance in hot humid conditions following whole body precooling. Med. Sci. Sports Exerc. 29, 943–949.

Borg, G.A., 1982. Psychophysical bases of perceived exertion. Med. Sci. Sports Exerc. 14, 377–381.

Castle, P.C., Macdonald, A.L., Philp, A., Webborn, A., Watt, P.W., Maxwell, N.S., 2006. Precooling leg muscle improves intermittent sprint exercise performance in hot, humid conditions. J. Appl. Physiol. 100, 1377–1384.

Cohen, J., 1992. A power primer. Psychol. Bull. 112, 155–159.

Costello, J.T., Algar, L.A., Donnelly, A.E., 2012. Effects of whole-body cryotherapy (−110 °C) on proprioception and indices of muscle damage. Scand. J. Med. Sci. Sports 22, 190–198.

Cotter, J.D., Sleivert, G.G., Roberts, W.S., Febbraio, M.A., 2001. Effect of pre-cooling, with and without thigh cooling, on strain and endurance exercise performance in the heat. Comp. Biochem. Physiol. A Mol. Integr. Physiol. 128, 667–677.

Crowe, M.J., O'Connor, D., Rudd, D., 2007. Cold water recovery reduces anaerobic performance. Int. J. Sports Med. 28, 994–998.

Davies, C.T., Mecrow, I.K., White, M.J., 1982. Contractile properties of the human triceps surae with some observations on the effects of temperature and exercise. Eur. J. Appl. Physiol. Occup. Physiol. 49, 255–269.

Davis, J.M., Bailey, S.P., 1997. Possible mechanisms of central nervous system fatigue during exercise. Med. Sci. Sports Exerc. 29, 45–57.

Dedering, A., Roos af Hjelmsater, M., Elfving, B., Harms-Ringdahl, K., Nemeth, G., 2000. Between-days reliability of subjective and objective assessments of back extensor muscle fatigue in subjects without lower-back pain. J. Electromyogr. Kinesiol.: Off. J. Int. Soc. Electrophysiol. Kinesiol. 10, 151–158.

Dewhurst, S., Macaluso, A., Gizzi, L., Felici, F., Farina, D., De Vito, G., 2010. Effects of altered muscle temperature on neuromuscular properties in young and older women. Eur. J. Appl. Physiol. 108, 451–458.

Duffield, R., Green, R., Castle, P., Maxwell, N., 2010. Precooling can prevent the reduction of self-paced exercise intensity in the heat. Med. Sci. Sports Exerc. 42, 577–584.

Duffield, R., Marino, F.E., 2007. Effects of pre-cooling procedures on intermittent-sprint exercise performance in warm conditions. Eur. J. Appl. Physiol. 100, 727–735.

Frohlich, M., Faude, O., Klein, M., Pieter, A., Emrich, E., Meyer, T., 2014. Strength training adaptations after cold water immersion. J. Strength Cond. Res./Natl. Strength Cond. Assoc..

Gagnon, P., Bussieres, J.S., Ribeiro, F., Gagnon, S.L., Saey, D., Gagne, N., Provencher, S., Maltais, F., 2012. Influences of spinal anesthesia on exercise tolerance in patients with chronic obstructive pulmonary disease. Am. J. Respir. Crit. Care Med. 186, 606–615.

Gonzales, B.R., Hagin, V., Guillot, R., Placet, V., Monnier-Benoit, P., Groslambert, A., 2014. Self-paced cycling performance and recovery under a hot and highly humid environment after cooling. J. Sports Med. Phys. Fit. 54, 43–52.

Gonzalez-Alonso, J., Teller, C., Andersen, S.L., Jensen, F.B., Hyldig, T., Nielsen, B., 1999. Influence of body temperature on the development of fatigue during prolonged exercise in the heat. J. Appl. Physiol. 86, 1032–1039.

Halder, A., Gao, C., Miller, M., 2014. Effects of cooling on ankle muscle strength, electromyography, and gait ground reaction forces. J. Sports Med. 2014, 520124.

Herrera, E., Sandoval, M.C., Camargo, D.M., Salvini, T.F., 2010. Motor and sensory nerve conduction are affected differently by ice pack, ice massage, and cold water immersion. Phys. Ther. 90, 581–591.

Herrera, E., Sandoval, M.C., Camargo, D.M., Salvini, T.F., 2011. Effect of walking and resting after three cryotherapy modalities on the recovery of sensory and motor nerve conduction velocity in healthy subjects. Rev. Bras. Fisioter. 15, 233–240.

Howe, A.S., Boden, B.P., 2007. Heat-related illness in athletes. Am. J. Sports Med. 35, 1384–1395.

Hunter, S.K., 2014. Sex differences in human fatigability: mechanisms and insight to physiological responses. Acta Physiol. (Oxf.) 210, 768–789.

Jutte, L.S., Merrick, M.A., Ingersoll, C.D., Edwards, J.E., 2001. The relationship between intramuscular temperature, skin temperature, and adipose thickness during cryotherapy and rewarming. Arch. Phys. Med. Rehabil. 82, 845–850.

Kollmitzer, J., Ebenbichler, G.R., Kopf, A., 1999. Reliability of surface electromyographic

measurements. Clin. Neurophysiol.: Off. J. Int. Fed. Clin. Neurophysiol. 110, 725–734.
Kotani, K., Tokunaga, K., Fujioka, S., Kobatake, T., Keno, Y., Yoshida, S., Shimomura, I., Tarui, S., Matsuzawa, Y., 1994. Sexual dimorphism of age-related changes in whole-body fat distribution in the obese. Int. J. Obes. Relat. Metab. Disord. 18, 207, (202).
Marino, F.E., 2002. Methods, advantages, and limitations of body cooling for exercise performance. Br. J. Sports Med. 36, 89–94.
Martin, P.G., Weerakkody, N., Gandevia, S.C., Taylor, J.L., 2008. Group III and IV muscle afferents differentially affect the motor cortex and motoneurones in humans. J. Physiol. 586, 1277–1289.
McDermott, B.P., Casa, D.J., Ganio, M.S., Lopez, R.M., Yeargin, S.W., Armstrong, L.E., Maresh, C.M., 2009. Acute whole-body cooling for exercise-induced hyperthermia: a systematic review. J. Athl. Train. 44, 84–93.
Merletti, R., Parker, P.J., 2004. Electromyography: physiology, engineering and non invasive applications.
Mesin, L., Cescon, C., Gazzoni, M., Merletti, R., Rainoldi, A., 2009. A bi-dimensional index for the selective assessment of myoelectric manifestations of peripheral and central muscle fatigue. J. Electromyogr. Kinesiol.: Off. J. Int. Soc. Electrophysiol. Kinesiol. 19, 851–863.
Minett, G.M., Duffield, R., Marino, F.E., Portus, M., 2011. Volume-dependent response of precooling for intermittent-sprint exercise in the heat. Med. Sci. Sports Exerc. 43, 1760–1769.
Nichols, A.W., 2014. Heat-related illness in sports and exercise. Curr. Rev. Musculoskelet. Med. 7, 355–365.
Nybo, L., 2008. Hyperthermia and fatigue. J. Appl. Physiol. 104, 871–878.
Nybo, L., 2012. Brain temperature and exercise performance. Exp. Physiol. 97, 333–339.
Palmieri, R.M., Garrison, J.C., Leonard, J.L., Edwards, J.E., Weltman, A., Ingersoll, C.D., 2006. Peripheral ankle cooling and core body temperature. J. Athl. Train. 41, 185–188.
Pointon, M., Duffield, R., Cannon, J., Marino, F.E., 2011. Cold application for neuromuscular recovery following intense lower-body exercise. Eur. J. Appl. Physiol. 111, 2977–2986.
Ranalli, G.F., Demartini, J.K., Casa, D.J., McDermott, B.P., Armstrong, L.E., Maresh, C.M., 2010. Effect of body cooling on subsequent aerobic and anaerobic exercise performance: a systematic review. J. Strength Cond. Res./Natl. Strength Cond. Assoc. 24, 3488–3496.
Robertson, C.V., Marino, F.E., 2017. Cerebral responses to exercise and the influence of heat stress in human fatigue. J. Therm. Biol. 63, 10–15.
Ross, M., Abbiss, C., Laursen, P., Martin, D., Burke, L., 2013. Precooling methods and their effects on athletic performance: a systematic review and practical applications. Sports Med. 43, 207–225.
de Ruiter, C.J., Jones, D.A., Sargeant, A.J., de Haan, A., 1999. Temperature effect on the rates of isometric force development and relaxation in the fresh and fatigued human adductor pollicis muscle. Exp. Physiol. 84, 1137–1150.
Schillings, M.L., Hoefsloot, W., Stegeman, D.F., Zwarts, M.J., 2003. Relative contributions of central and peripheral factors to fatigue during a maximal sustained effort. Eur. J. Appl. Physiol. 90, 562–568.
Schniepp, J., Campbell, T.S., Powell, K.L., Pincivero, D.M., 2002. The effects of cold-water immersion on power output and heart rate in elite cyclists. J. Strength Cond. Res./Natl. Strength Cond. Assoc. 16, 561–566.
Tyler, C.J., Sunderland, C., Cheung, S.S., 2015. The effect of cooling prior to and during exercise on exercise performance and capacity in the heat: a meta-analysis. Br. J. Sports Med. 49, 7–13.
Uckert, S., Joch, W., 2007. Effects of warm-up and precooling on endurance performance in the heat. Br. J. Sports Med. 41, 380–384.
Versey, N.G., Halson, S.L., Dawson, B.T., 2013. Water immersion recovery for athletes: effect on exercise performance and practical recommendations. Sports Med. 43, 1101–1130.
Wegmann, M., Faude, O., Poppendieck, W., Hecksteden, A., Frohlich, M., Meyer, T., 2012. Pre-cooling and sports performance: a meta-analytical review. Sports Med. 42, 545–564.
Xu, L., Zhang, D., Xian, X., 1997. Fractal dimensions of coals and cokes. J. Colloid Interface Sci. 190, 357–359.

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