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ABSTRACT:

Previous research suggests cooling distal to the working agonist muscles during the inter-set rest periods of high-intensity resistance exercise may facilitate improved performance via improving metabolic conditions of contractile machinery. However, these studies haven't directly measured indicators of metabolic conditions. Therefore, the aim of this study was to compare two palm-cooling conditions to a thermoneutral condition during high-intensity resistance exercise and subsequent effects on physiological and metabolic responses and exercise performance**.** Eleven healthy, resistance-trained, young males (20-36 years old) performed four sets of bench press exercise to exhaustion at 80% 1RM each separated by three minutes of passive recovery. Palm-cooling (10°C [TEN] or 15°C [FTN]) or thermoneutral (28°C [CON]) conditions were applied for sixty seconds during the recovery interval of each set in a randomised, double-blind fashion, with four days recovery between experimental conditions. There were no differences ($p>0.05$) in volume-load between experimental conditions across all sets. Mean repetition velocity and force of the bench press declined significantly following set 1 in all conditions ($p<0.05$), but there were no differences between conditions. Lactate, heart rate and RPE systematically increased from sets 1-4, however, there were no significant differences ($p>0.05$) between any of the conditions. Palm cooling at either 10 or 15°C had no observable effects on physiological and metabolic responses during exercise, nor any effect on bench press performance or volume-load compared to a thermoneutral condition. Therefore, cooling cannot be currently recommended as an ergogenic strategy to enhance acute bench press performance or mitigate fatigue during high-intensity resistance training.

Key words: conduction; convection; lactate; metabolism; muscle; agonist

INTRODUCTION:

Exercise volume, i.e. the total amount of work performed by the muscle(s) is known to be a key component of a resistance training exercise program with the aim of inducing muscle hypertrophy (9, 18), which may also be a contributory factor for increased strength (19). Therefore, acute manipulation of exercise variables, or provision of ergogenic aids to elicit increases in exercise volume, may improve the efficacy and outcomes of a resistance training program. As such, there have been reports in the exercise science literature that including cryotherapy, via the application of cooling distal to the working muscle, improves the total volume of exercise performed compared to a control (thermoneutral) condition in young, resistance trained males and females (4, 11, 12). In these studies, the researchers employed cooling in the form of palm-cooling (e.g. for upper body exercise such as bench press) or sole-cooling (e.g. for lower body exercise such as leg press) during the inter-set rest period of high-intensity resistance exercise. They found by applying a cooling apparatus of ~10^{o}C to the palms or soles during four sets of resistance exercise to exhaustion at 85%-90% 1RM resulted in an increased number of repetitions completed, volume-load and root mean squared electromyography (RMS-EMG) amplitude compared to a thermoneutral condition. However, these findings have not been universal. Batra et al. (2) and Esteves et al. (8) found that distal application of cooling during resistance exercise to fatigue did not result in acute resistance exercise performance (i.e. increased volume-load) or EMG amplitude compared to a control condition. Kwon et al. (11, 12) and Cai et al. (4) proposed that based off their studies' results, that a neural mechanism is responsible for the cooling-induced increase in exercise volume, as this was accompanied by an increased RMS EMG activity during resistance exercise in the cooling condition. However, these studies used inappropriate EMG normalisation techniques including , normalising the RMS EMG amplitude to the task performance (bench press) instead of a maximal voluntary isometric contraction, unnecessarily normalising spectral data, and using only a single electromyograms to compare pre-to-post exercise EMG amplitudes (15) raising questions over the interpretability of their results and veracity of their conclusions. Indeed, McMahon et al. (15) recently showed that there were no significant differences between two cooling conditions and a thermoneutral condition regarding RMS EMG amplitude nor spectral frequencies during resistance exercise when appropriate EMG normalisation methods were employed. Therefore, further investigations are needed to ascertain the ergogenic potential and mechanism of cooling application distal to the muscle during high-intensity resistance exercise to exhaustion.

Arterio-venous anastomoses (AVAs) are found in glabrous skin of the palms and soles of humans and serve as an important site of temperature control in the thermoneutral zone (22), and thus are the choice of site for the application of distal cooling. AVAs have large diameter inner walls, are densely innervated by adrenergic axons, and are a direct connection between arteries and veins. When open they permit shunting of blood directly to the venous plexuses of limbs (22). Grahn et al. (10) showed that application of palm cooling (15°C) during a 6-week upper body resistance training program resulted in significantly greater strength and very large acute volume-load improvements compared to a control group. The authors speculated that the palm cooling condition resulted in the cooling of blood circulated to the muscle (e.g. from the venous plexus) which contributed to superior temperature-dependent activity of intramuscular enzymes involved in ATP production, such as muscle pyruvate kinase (MPK), thus facilitating maintenance of contractile force during resistance exercise compared to control. Additionally, peripheral fatigue induced by accumulation of metabolic by-products during ATP production (e.g. during high-intensity resistance exercise) also inhibits muscle contractile velocity via direct alteration of actomyosin function (7). However, to date no palm cooling studies have investigated the metabolic and physiological responses (such as lactate production) to palm cooling in conjunction with resistance exercise performance characteristics (e.g. maintenance of performance force and velocity) in addition to the oft-reported volume-load performed of the local agonist muscle groups.

In the studies that have reported a positive outcome of palm cooling on resistance exercise performance (10-12), it appears that palm cooling at both 10°C and 15°C may potentially provide an ergogenic effect for improving acute resistance exercise performance. However, to date no studies have directly compared the physiological and metabolic responses in addition to exercise performance of inter-set cooling using either a 10°C or 15°C compared to a control (thermoneutral) condition. Therefore, the aim of the current study is to investigate the acute effects of palm cooling application on physiological and metabolic responses and exercise performance, specifically comparing the effects of cooling using 10°C or 15°C to a control (thermoneutral) condition.

METHODS:

Experimental Approach to the Problem

The study used a within-subjects, randomized, controlled, counterbalanced design in order to effectively assess differences in physiological and metabolic responses and bench press performance variables under three different conditions. Participants completed a traditional resistance training protocol of four sets of bench press exercise at 80% 1RM to volitional exhaustion in each set, interspersed by three minutes of passive recovery. Exercise load, tempo, inter-set recovery duration and inter-set condition application duration were all controlled throughout the study; therefore, the inter-set recovery condition (independent variable) was the only altered variable between laboratory sessions. Palm cooling or thermoneutral (control) conditions were employed for 60 s during the inter-set recovery period. The study design, loading scheme and protocol used are largely replicative of those already evident in cooling literature. The dependent variables recorded were volume-load lifted, force and velocity via a linear position transducer for bench press performance, heart rate, blood lactate and rating of perceived exertion (RPE).

Participants:

An a priori sample size calculation was performed using G*Power software (version 3.1.9.7) (21). It was set to a within factors repeated-measures analysis of variance (ANOVA) with a desired power (1- ß) of 0.80 and assuming an alpha (α) level of 0.05. As a result, a specified sample size of 12 participants was deemed satisfactory to detect a large effect size ($\eta_p^2 = 0.14$), which is representative of changes in the volume-load lifted attributed to palm cooling in previously published research (11, 12).

Twelve healthy, male volunteers volunteered for this study, however due to Covid-19 related issues, one participant dropped out prior to the beginning of the study. Therefore, 11 (age, 23 ± 5 years; mass, 86.8 ± 18.4 kg; height, 1.79 ± 0.08 m) volunteers completed the study. Participants were recruited from the local university campus and gyms using posters, e-mails and word of mouth. To be eligible for the study, individuals needed to be between 18–39 years of age and currently participating in upper body resistance training at least once per week, with a minimum of one year of upper body resistance training experience. The resistance training experience for the study sample was 5 ± 2 years. Inclusion criteria included not having any musculoskeletal or neurological disorders, being free from injury and not supplementing with any ergogenic aids either 3 months prior to or during the study. Following a pre-screening physical activity questionnaire to ensure eligibility, participants were provided with an information sheet, outlining the full experimental procedure and risks involved. All participants gave their written informed consent to participate. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ulster University School of Sport Ethics Committee.

Experimental design:

The experimental design was a randomized, double blind, controlled, crossover study, which was largely replicative of the designs used in previous palm and sole cooling studies (4, 11, 12) and has been detailed previously (15). This included four experimental visits to the laboratory, each separated by four days. The first laboratory visit included establishing each participant's 1RM and familiarizing them with the experimental exercise protocols. Prior to 1RM testing, no participants had participated in upper body exercise within at least 48 hours, nor had they consumed any caffeine, stimulants or other ergogenic aids with the potential to acutely modulate resistance exercise performance within the previous 24 hours.

Procedures

One-Repetition Maximum (1RM) Testing

Before performing an attempt on their 1RM, participants were asked to estimate their 1RM based on their most recent training performance. From this estimation participants performed a standardized warm-up of six repetitions at 50% 1RM, four repetitions at 80% 1RM, one repetition at 85% 1RM and one repetition at 90% 1RM with 60-seconds between sets. Following 3 mins of passive recovery participants then proceeded to attempt their 1RM. They were asked to use their preferred barbell grip width that they used to habitually perform the bench press during their own training history, which was assessed and maintained during each subsequent 1RM attempt. The load which was added to the bar was estimated and agreed upon by the primary investigator and participant. Each participant was allowed 3 mins recovery between each 1RM attempt. All participants achieved their 1RM within ≤4 lifts. A 1RM was defined as the maximal amount of weight lifted during a complete, full range-of-motion repetition of the bench press exercise. Full range-of-motion for the 1RM and experimental trials was defined as lowering the bar to the xiphoid process and raising the bar until full extension of the elbow had occurred. Safety bars and two spotters were employed during the 1RM attempts with full verbal encouragement provided during each attempt. Once the 1RM had been established, participants were allowed five minutes of passive recovery, before completing one set of supine bench press exercises to exhaustion at 80% 1RM for familiarization. Each participant completed three experimental conditions 1) palm-cooling at 10^{o}C (TEN), 2) palm-cooling at 15^{o}C (FTN), and a thermoneutral control condition (CON) in a randomized order, recorded and managed by a researcher independent to the study. The experimental conditions of each participant's visit were not revealed to the investigators or participants until post analysis. During each of the three experimental trial days, participants performed four sets of bench press at 80% 1RM to volitional exhaustion, separated by 3 mins of passive recovery whilst the palm was exposed to one of the experimental conditions. During each of the four visits, participants performed the exercise protocol at the same time of the day to minimise any potential effects of circadian rhythm on muscle performance. Three days existed between the 1RM/ familiarization session and the first experimental trial. All sessions were carried out under identical laboratory conditions (19^{o}C, 65% Relative humidity, 1008 hPa).

Experimental Exercise Protocol

Prior to commencing the experimental exercise protocol on any of the three trial days, participants completed a standardized warm-up of five repetitions at 50% 1RM, four repetitions at 70% 1RM and one repetition at 80% 1RM. Participants rested for 3 mins before performing an MVIC for EMG normalization (as part of separate study). Upon completing the MVIC, participants rested for a further 5 mins and then performed four sets of as many repetitions as possible until volitional exhaustion at 80% 1RM interspersed with three minutes of recovery. Verbal encouragement was provided at all times by the lead investigator. A repetition was not counted if it violated the previous definition of a successful repetition. Repetitions were performed with a 2 s eccentric, 2 s concentric phase tempo monitored via a metronome, and the number of successful repetitions were recorded. Exercise was terminated and termed volitional exhaustion when a full repetition could not be completed, that is the lowering and raising of the bar through the full range-of-motion as previously outlined.

Experimental Conditions

Palm cooling and the thermoneutral condition were induced by the Core TX Thermal Exchange palm cooling device (CET Ltd, Dromore, Northern Ireland). During each of the 3-min recovery periods between resistance exercise sets, participants placed their palm over a large circular opening in the roof of the device, forming a water-tight seal. The cooling device then expelled a single, continual vertical jet of water up to the palm of the hand from the basin below. Palm cooling or thermoneutral water was applied to the palm surface for 60s during the inter-set rest periods as per manufacturer’s recommendation. During the recovery, palm cooling or thermoneutral water was applied from the 30th to the 90th second of the 3 min period. This 30 s time delay from the cessation of exercise to cooling initiation was due to the time taken needed to transition from the bench press to the cooling device and for some of the immediate post-exercise physiological measures to take place. The water temperature was maintained at 10°C (TEN), 15°C (FTN) and 28°C (CON) for the two experimental and control trials respectively. Palm temperature was assessed via an infrared skin thermometer (Berrcom JXB-

178, Nansha, GuangZhou, China) at 3 cm from the skin surface after approximately 1 s. Palm temperatures were initially assessed during the familiarization session. Participant's palm temperatures were taken three times before any exercise had commenced 10 mins after reporting to the laboratory. The mean of each participant's palm temperature was then used to calculate the thermoneutral condition rather than a pre-planned thermoneutral condition as used in other studies. The mean thermoneutral palm temperature was 28.0 ± 2.8°C. The reliability of the device was excellent as shown previously (14). During each of the experimental trials, palm temperature was recorded immediately post exercise (within ~6-10 s), immediately post condition cooling/thermoneutral exposure following drying of the palm, and at the end of the recovery period.

Volume-Load

Repetitions were performed and monitored with a 2-second eccentric, 2-second concentric phase tempo regulated via a metronome for as long as possible. The number of successful repetitions from each set were recorded. Exercise volume-load was calculated as the product of the load pressed during the exercise multiplied by the number of successful repetitions completed, multiplied by the number of sets, as per previous palm cooling studies.

Blood Lactate Quantification

To obtain blood lactate, an alcohol wipe (Alcotip swab, Universal Hospital Supplies, London, UK) was used to cleanse the participant's finger, and a sterile lancet (Accu Chek, Roche, Mannheim, Germany) was used to pierce the skin of the finger to produce blood. A Lactate Pro 2 lactate strip (Arkray, KDK Corp., Shiga, Japan) collected the blood, which was then inserted into a Lactate Pro 2^{TM} lactate analyser (Arkray, KDK Corp., Shiga, Japan), to determine the lactate content of the participant's blood. Lactate measures were taken at rest prior to exercise, during the first 20s immediately following the completion of the set and within the last 20s immediately before cessation of the 3-minute rest period.

Heart Rate and RPE

Heart rate was recorded using a Polar H7 heart rate monitor (Polar, Kempele, Finland) and a Polar RS400 watch, and was taken at rest prior to the first resistance exercise set, immediately following the cessation of each set (within ~5secs, timepoint 'a') and within the last 5secs immediately before cessation of the 3-minute rest period (timepoint 'b'). RPE (rate of perceived exertion) was provided by each participant via the Borg scale, and was taken immediately following cessation of each exercise set.

Mechanical Performance Characteristics (Mean Repetition Velocity & Force)

Mechanical performance characteristics were assessed via a commercially available linear position transducer (LPT) consisting of a floor unit, made up of a spring-powered retractable cable that is wound on a cylindrical spool coupled to the shaft of an optical encoder (GYM Aware Power Tool, Kinetic Performance Technologies, Canberra, Australia). The floor unit was placed on the floor perpendicular to the left collar of the barbell. The other end of the cable was vertically attached to the barbell (immediately proximal to the left collar) using a velcro strap. Vertical displacement of the barbell was measured from the rotational movement of the spool. Displacement data were time-stamped at 20 ms time points to obtain a displacement-time curve for each repetition, which was downsampled to 50 Hz for analysis. The sampled data were not filtered. Mean velocity was determined as the change in barbell position with respect to time. Mean force (MF) was determined by multiplying the system mass with acceleration (rate of change in instantaneous velocity), where system mass was the barbell load plus the body mass of the participant. Data were transmitted through Bluetooth to a tablet (iPad; Model A1474, Apple, Inc., Cupertino, CA, USA) using the GymAware v2.1.1 app. The participant's body mass and the barbell load used were entered into the GymAware app at the beginning of each experimental trial (16).

Statistical Analysis

All statistical analysis was performed using JASP software (version 0.14.1; JASP, Amsterdam, The Netherlands). Prior to parametric tests, the normality of distributions was determined by the Shapiro-Wilk test. A two-way (temperature condition [CON, TEN and FTN] x measurement time point) within-within repeated-measures ANOVA evaluated the temperature effects and time effects on palm temperature, MV, MF, blood lactate, heart rate and RPE data. Where Mauchly's assumptions of sphericity were violated, Greenhouse-Geisser corrections were used. A one-way (temperature condition [CON, TEN and FTN]) repeated-measures ANOVA was used to evaluate the temperature effects on exercise volume. Where applicable, *post hoc* analysis was performed using Holm's corrections (5). Partial eta squared (η_p^2) statistics were calculated as a measure of effect size, where 0.01 = small; 0.06 = medium; and 0.14 = a large effect. The α-level for statistical significance was set at $p < 0.05$. Data were presented as mean ± SD, unless otherwise stated.

RESULTS:

Volume-Load

The one-way ANOVA revealed no significant differences in the overall exercise volume-load ($F_{2,20} = 0.45$, $p = 0.561$, $\eta_p^2 = 0.04$, Figure 1) completed between the temperature conditions.

INSERT FIGURE 1 HERE

Blood Lactate

There was a significant main effect of time ($F_{8,80} = 134.5$, $p < 0.001$, $\eta_p^2 = 0.83$), with blood lactate progressively increasing from the first set to the last. While the main effect for temperature ($F_{2,20} = 1.73$, $p = 0.203$, $\eta_p^2 = 0.15$) and the time x temperature interaction revealed no significant effects ($F_{16,160} = 0.82$, $p = 0.661$, $\eta_p^2 = 0.08$, Figure 2). Post-hoc analysis revealed that at each time point, blood lactate was significantly higher than at rest ($p < 0.05$). In addition, at each post-exercise time point, blood lactate was significantly different from all equivalent time points ($p < 0.001$). Post-recovery blood lactates were only significantly higher when compared to Set 1 ($p < 0.01$).

INSERT FIGURE 2 HERE

INSERT FIGURE 3 HERE

Heart Rate

There was a significant main effect of time ($F_{8,80} = 161.9$, $p < 0.001$, $\eta_p^2 = 0.94$), with heart rate progressively increasing from the first set to the last (Figure 3). While the main effect for temperature ($F_{2,20} = 0.05$, $p = 0.955$, $\eta_p^2 = 0.01$) and the time x temperature interaction revealed no significant effects ($F_{16,160} = 0.77$, $p = 0.716$, $\eta_p^2 = 0.07$). Post-hoc analysis revealed that at each time point, heart rate was significantly higher than at baseline ($p < 0.05$). In addition, post-recovery heart rate at Set 3 was significantly higher than at Set 1 ($p < 0.001$).

RPE

The two-way ANOVA revealed a significant main effect of time ($F_{3,30} = 42.1$, $p < 0.001$, $\eta_p^2 = 0.81$), with RPE progressively increasing from the first set to the last (Table 1). While the main effect for temperature ($F_{2,20} = 1.3$, $p = 0.300$, $\eta_p^2 = 0.11$) and the time x temperature interaction revealed no significant effects ($F_{6,60} = 0.58$, $p = 0.742$, $\eta_p^2 = 0.05$). Post-hoc analysis revealed that at each time point, RPE was significantly different from all other time points ($p < 0.05$).

Palm Temperature

Percentage change in palm temperature showed main effects of time ($F_{10,100} = 55.3$, $p < 0.001$, $\eta_p^2 = 0.85$), temperature ($F_{2,20} = 90.5$, $p < 0.001$, $\eta_p^2 = 0.90$) and the time x temperature interactions ($F_{20,200} = 35.8$, $p < 0.001$, $\eta_p^2 = 0.78$, Table 1). Post-hoc analysis revealed that at each time point, palm temperature during the thermoneutral condition was significantly higher than the other two conditions, with the exception of post-exercise 2, 3 and post-exercise 4 for the 15 degree condition. In addition, palm temperature during the 10 degree condition was significantly lower than the 15 degree condition at post-cooling 2, 3 and 4 ($p < 0.05$).

INSERT TABLE 1 HERE

Mechanical Performance

There was a significant main effect of time ($F_{3,30} = 12.6$, $p < 0.001$, $\eta_p^2 = 0.56$), with velocity progressively decreasing from the first set to the last (Figure 4) while the main effect for temperature ($F_{2,20} = 1.00$, $p = 0.386$, $\eta_p^2 = 0.09$) and the time x temperature interaction revealed no significant effects ($F_{6,30} = 1.38$, $p = 0.275$, $\eta_p^2 = 0.12$). Post-hoc analysis revealed that at each time point, velocity was significantly lower than during Set 1 ($p < 0.05$).

There was a significant main effect of time ($F_{3,30} = 8.6$, $p = 0.006$, $\eta_p^2 = 0.46$), with force progressively decreasing from the first set to the last. While the main effect for temperature ($F_{2,20} = 2.2$, $p = 0.135$, $\eta_p^2 = 0.18$) and the time x temperature interaction revealed no significant effects ($F_{6,30} = 0.40$, $p = 0.651$, $\eta_p^2 = 0.04$). Post-hoc analysis revealed that force at Set 4 was significantly lower than all other time points. ($p < 0.05$).

INSERT FIGURE 4 HERE

DISCUSSION:

The aims of the current study were to investigate the modulation of physiological and metabolic responses and exercise performance via palm cooling during high intensity resistance exercise compared to a thermoneutral condition, and whether there were any further differences within application of palm cooling conditions at either 10°C or 15°C. The main findings of the current study are that not only were there no differences between palm cooling at 10°C and 15°C, neither of the experimental conditions were different to the control condition in terms of physiological and metabolic responses or exercise performance despite significantly different palm temperatures. Thus, the use of palm cooling is not currently recommended to reduce the physiological strain of high-intensity bench press exercise within the parameters of the study design.

To date, this is the first study to measure any metabolic variable in a palm or sole cooling study. Our lactate results show that there is a strong metabolic component present in 4 sets at 80% 1RM to exhaustion in the bench press. The pectoral, anterior deltoid and triceps brachii are relatively small muscle masses compared to the larger muscles found in the lower limbs. However, mean lactate was ~8 $m.mol/L^{-1}$ in each of the conditions by set 4, with lactate values in some participants being > 12$m.mol/L^{-1}$, which are comparable to whole body exercise primarily involving the much larger lower limb muscle masses. Lactate systematically rose from rest values through each set and following the final set. This would suggest at the cellular level that a significant amount of anaerobic glycolysis is taking place within the muscle groups and therefore metabolite accrual may be potentially contributing to peripheral muscle fatigue (although lactate not necessarily playing a causal role in fatigue) (1). The results of the current study also demonstrate that palm cooling was not able to attenuate the exercise-induced decline in mean repetition velocity or force. Currently, the authors used a metronome to control for repetition velocity to standardise across sets and between participants. Had this not been done so, then fluctuations in repetition velocity, excessively rapid or excessively slow repetitions all could have affected the results independently of the palm temperature effects. However, at some point, the combination of several physiological factors (central activation, excitation-contraction coupling, metabolite accrual etc.) would lead to a reduction in muscle contractile force and speed (3), therefore controlling repetition velocity until this point was an important aspect. Previous work from the current authors demonstrated that there were no differences in RMS-EMG amplitude nor spectral frequencies between palm-cooling and thermoneutral conditions (15), suggesting that neural factors such as muscle activation and muscle fibre conduction velocity were not altered by condition. Muscle metabolites produced during ATP production (ADP, Pi, H+ ions etc.) have the propensity to reduce the activity of cross-bridge cycling rate constants (14) and inhibit excitation-contraction coupling processes during fatigue, leading to reductions in muscle force and contractile velocity (13). However, in the current study, there were no group × time interactions in neither lactate accumulation, mean repetition velocity, mean repetition force or volume-load, suggesting a lack of ergogenic impact of cooling on this aspect of metabolism and ultimately exercise performance. This is in contrast to previous studies from Kwon et al. (11, 12) and Cai et al. (4) who found that total exercise volume was increased in palm and sole-cooling conditions respectively. In a similar vein, heart rate responses to exercise are reflective of those previously reported in palm cooling studies (11, 12), whereby heart rate displays a main effect of exercise but no experimental group differences between control and palm cooling conditions. RPE also showed a main effect of time but no experimental condition interaction in the current study. Kwon at al. (12) found that RPE was significantly lower, but only in the 2nd set out of 4 sets, when comparing palm-cooling to thermoneutral and observed significant overall differences in bench press performance in the palm-cooling condition. Cai et al. (4) also reported no effects of cooling on RPE but found a significant increase in exercise performance in the cooling condition. Finally, Batra et al. (2) found RPE to be significantly lower in the cooling condition compared to thermoneutral but observed no effects of condition on exercise performance. Therefore, the effects of cooling on the relationship between perceptions of exercise intensity and exercise performance seem to be conflicting, with exercise performance being improved both with and without differences in RPE.

A potential mechanism for cooling to mediate an effect on performance is through improving the heat capacity of blood circulating to the working musculature. Arterio-venous anastomoses (AVAs) are found in glabrous skin of the palms and soles of humans and serve as an important site of temperature control in humans (22). They are direct connections between small arteries and veins and when open they permit shunting of blood directly to the venous plexuses of limbs. Various contractile mechanisms, but in particular enzymatic activity related to ATP production during exercise, are sensitive to temperature regarding muscle function(1) and cooling of the hand has the ability to alter superficial local muscle temperatures of the limb (6). Our protocol was successful in achieving significantly different palm temperatures between conditions, with post-cooling reductions of ~30% (TEN) and ~20% (FTN) in palm temperature compared to ~18% increase in CON at the same time-point within the recovery period. Our previous data demonstrated that in absolute terms, this was equivalent to post-cooling palm temperatures of ~16°C and ~19°C in TEN and FTN respectively versus ~28°C in CON. The mean palm temperatures achieved during the interest recovery period in TEN and FTN are comparable to those previously reported in palm cooling studies (11, 12, 15). Grahn et al. (10) suggested that from the results of their study, this was one of the potential mechanistic links between palm cooling and resistance exercise performance, via increasing the temperature-dependent activity of intramuscular enzymes such as pyruvate kinase. Whilst palm-cooling has been shown to improve resistance exercise performance in a hot environment (10), the results from the current study conducted in a thermoneutral condition (room temperature) would suggest this is unlikely to be the main mechanism responsible for improved performance. This is supported by our lactate results and the discussion from the previous paragraph. This is further supported by Kwon et al. (11) who showed that both palm cooling (10°C) and palm heating (45°C), which would result in an increased local muscle temperature, improved bench press volume-load, number of repetitions and RMS EMG amplitude versus control, with no differences between palm cooling or heating conditions.

If a neural mechanism is responsible for the ergogenic response to exercise with cooling, rather than one that is metabolic in nature, as has been proposed by previous researchers (4, 11, 12, 20), this may also have implications for the intensity of loading in which cooling should be applied in study designs. In the studies that have employed surface EMG techniques and have reported significantly greater EMG amplitudes in the cooling conditions compared to control (4, 11, 12), the authors have used a loading intensity of 85-90% 1RM. Whilst the Kwon et al. studies (11, 12) used a flat 85% 1RM loading scheme throughout each set, Cai et al. (4) used a pyramid loading scheme progressing from 85% 1RM for the first two sets, 87.5% 1RM for the third set and 90% 1RM for the final set. All of the studies, including the current study, that have not reported an ergogenic effect of inter-set cooling have used loading intensities of approximately 70-80% 1RM. In short-term, high intensity contractions, motor unit recruitment and discharge rates are increased with increasing contractile intensity (17). It may be that slightly lower loading intensities of 70-80% 1RM may include both a metabolic and neural component due to the number of contractions performed in total, such as shown in the current lactate results. If the scenario of a combination of both metabolic and peripheral component was present in the 70-80% 1RM loading ranges, then the acute effects of peripheral fatigue on the contractile mechanisms that are non-neural based (such as metabolite accrual) may play some contributory role that cooling has a reduced impact on. However, without any evidence of the metabolic conditions induced in loading of ≥85% 1RM to compare to, this is purely speculative at this juncture. Taking the results of the current study into consideration, and those of previous palm and sole-cooling studies, the exact ergogenic mechanism and pathways by which cooling exerts its effects (if there is one), remains elusive. Using more advanced techniques such as high-density EMG (HD-EMG) and interpolation twitch techniques for neural factors and possibly muscle biopsy work for metabolic factors may be required to uncover the effects of cooling during high-intensity resistance exercise.

PRACTICAL APPLICATIONS:

The results of the current study demonstrate that high intensity resistance exercise increases the physiological and metabolic demands on skeletal muscle, resulting in progressively decreasing repetition velocity and force. In addition, there was no ergogenic effects of the application of inter-set palm cooling on physiological responses, exercise performance or total exercise volume compared to a control condition, which is contradictory to some previous literature. Our results demonstrate that the previously reported positive acute effects of palm-cooling on upper-body resistance exercise performance should be interpreted cautiously by sports scientists/ strength & conditioning coaches seeking to enhance athlete physical preparation.

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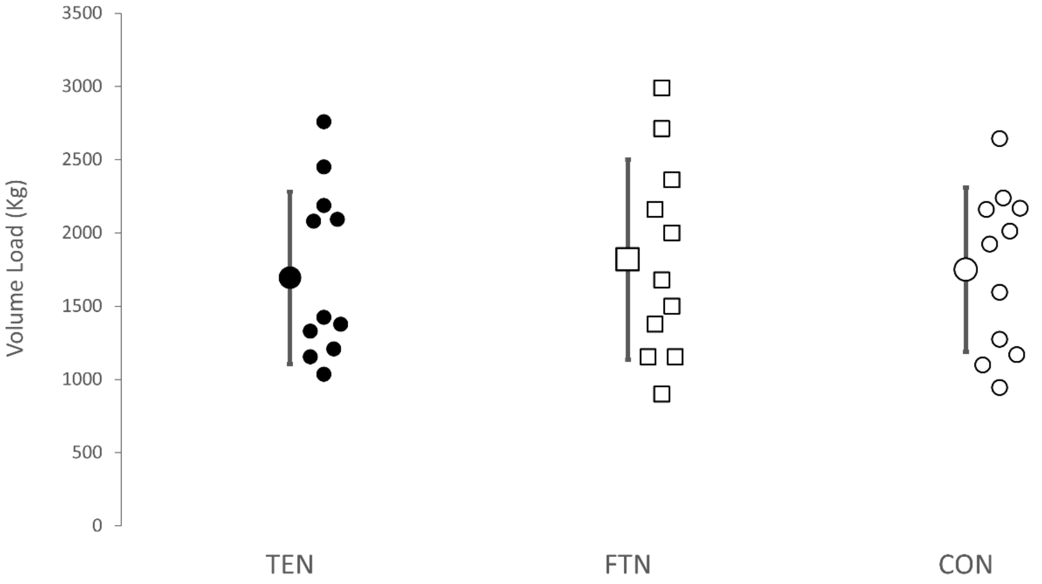
FIGURES:

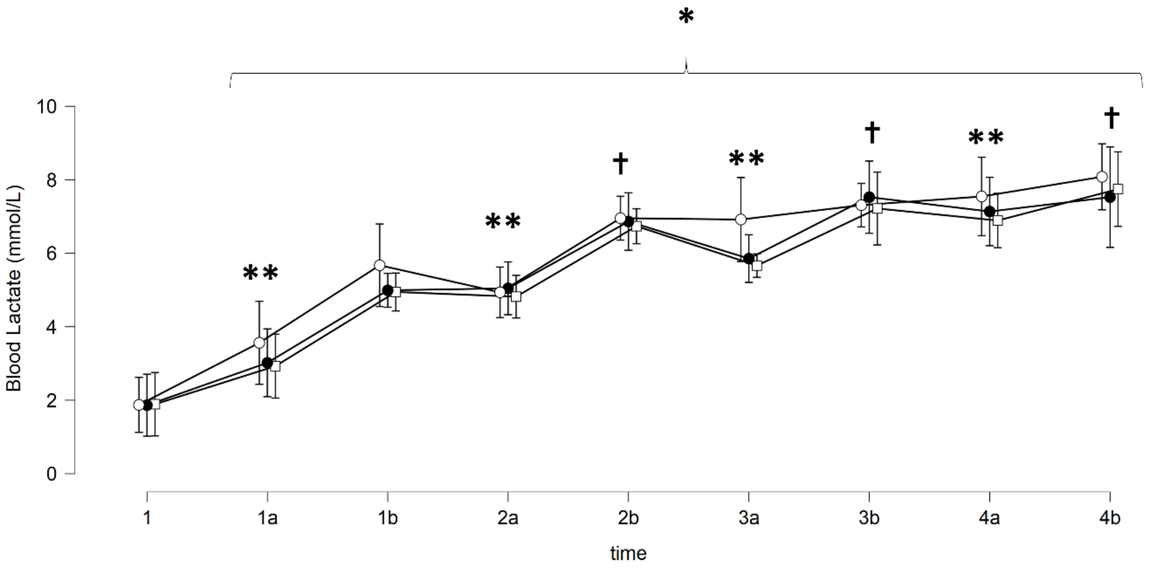
Figure 1: Volume-Load completed for each group.

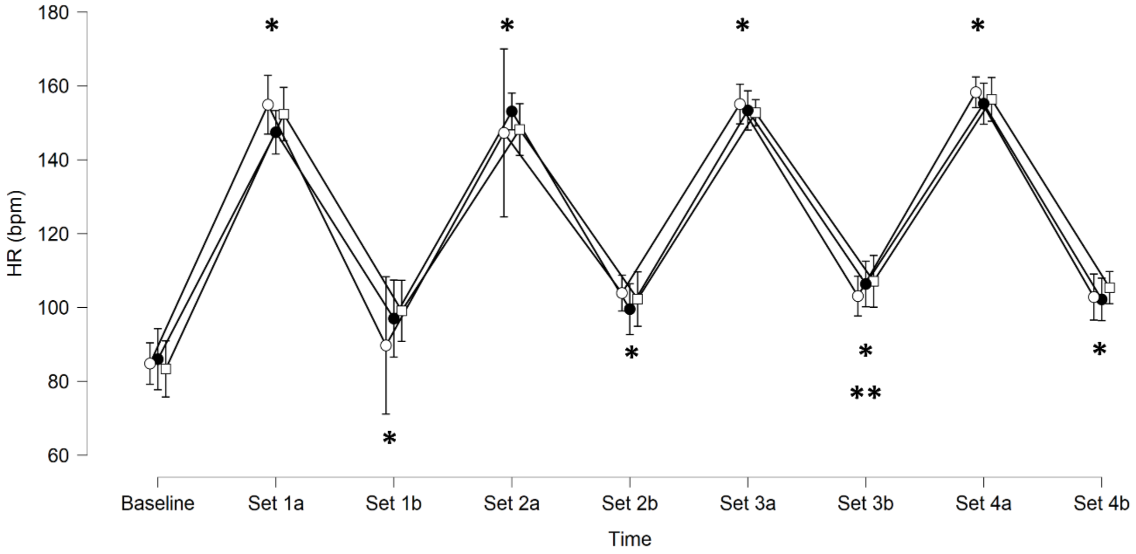
Figure 2: Blood Lactate for TEN (black circles), FTN (white squares) and CON (white circles) groups in each set. * Significantly different ($p<0.05$) to baseline at all timepoints. ** Significantly different ($p<0.05$) to all other Post-exercise (a) timepoints. † Significantly different ($p<0.05$) to Set 1b.

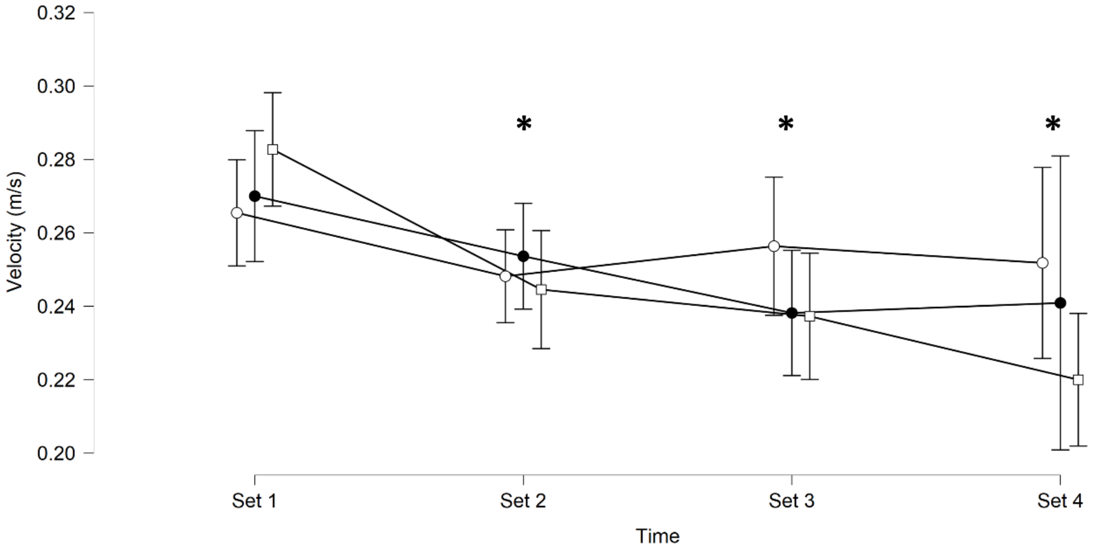
Figure 3: Heart Rate for TEN (black circles), FTN (white squares) and CON (white circles) groups in each set. * Significantly different ($p<0.05$) to baseline. ** Significantly different ($p<0.05$) to Set 1b.

Figure 4: Mean Velocity for TEN (black circles), FTN (white squares) and CON (white circles) groups in each set. * Significantly different ($p<0.05$) to Set 1.




*
10
8
6
4
2
0
Blood Lactate (mmol/L)
**
**
†
**
†
**
†
1
1a
1b
2a
2b
3a
3b
4a
4b
time


180
160
140
120
100
80
60
HR (bpm)
*
*
*
*
*
*
*
**
*
Baseline
Set 1a
Set 1b
Set 2a
Set 2b
Set 3a
Set 3b
Set 4a
Set 4b
Time


0.32
0.30
0.28
0.26
0.24
0.22
0.20
Velocity (m/s)
*
*
*
Set 1
Set 2
Set 3
Set 4
Time