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LOCAL HEATING AND COOLING WITH ISOMETRIC EXERCISE TRAINING AS A STRATEGY TO IMPROVE SIZE AND PERFORMANCE

Feng He*, Weston Soudan, Nathan Chang, Ryan K. Perkins
Department of Kinesiology, California State University, Chico

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Feng et al. The purpose of this study was to explore the effects of local heating and cooling with isometric exercise training of upper arm and forearm. College-aged (n=12; 21±1 y) volunteers performed 4-wk isometric exercise training of the non-dominant arm (upper arm, isometric bicep curl; forearm, handgrip), while the dominant arm served as the control. Training was performed 3x/wk and consisted of 1 set of isometric handgrip and bicep curl until volitional exhaustion at 60% pre-training MVC for the forearm (handgrip) and 1RM for the upper arm (bicep curl). Randomized ordering of heating (40°C; 15 min) and cooling (12°C; 15 min) preceded each training session. Indirect assessment of muscle size (fat-free cross-sectional area [FFCSA]) was made before and after the training period via skin fold and limb circumference measures. Biceps 1RM increased significantly ($p < 0.05$) after the intervention in both conditions (trained: +6%; control: +7%), whereas only the control arm increased time to fatigue (+40%; $p < 0.05$). FFSCA of the upper arm remained unchanged (p>0.05) in both conditions. An effect of time was noted for forearm MVC (+8%; $p < 0.05$), while both groups increased ($p < 0.05$) time to fatigue (trained: +82%; control: +64%). A trend toward an effect of time was also noted for FFCSA of the forearm (+3%; p <.10). While the intervention employed here led to many notable adaptations, the thermal stress did not appear to exert a clear benefit. Coupled with the practicality and feasibility, improving size and performance in such a short time frame has therapeutic and ergogenic aid implications.

Key Words: isometric exercise, heating and cooling, fatigue, exercise performance, skeletal muscle

Introduction

Modulation of body temperature appears to have originated as far back as 3500 BC by Edwin Smith Papyrus and later by the Hippocratic school of medicine as early references are made regarding the impact of cold as a therapeutic modality (Wang et al., 2006). Interest in cold stress as an ergogenic aid is much more recent as it was not until World War II and the decades that followed that concerted scientific efforts were made (Kelso & Reinhardt, 1943; Walker, 1949). To this point, work on cold stress (e.g., cold-water immersion, etc) has been predominantly directed towards maintaining core temperature during prolonged aerobic exercise (AE). This makes sense given the heat-producing nature of AE and the tendency of this heat to accumulate and increase core temperature. A consequence of this predilection of exploring the effects of cold stress in the context AE has resulted in comparatively little attention devoted to the potentially ergogenic effects of cold stress on resistance exercise (RE). Given the longstanding presumption that heat accumulation/application with exercise is not favorable, even less consideration has been given to potential beneficial interactions between heat and cold on RE.

Though not all studies agree, substantial literature exists showing application of cold directly to an exercising region of muscle acutely reduces maximal strength (Bergh & Ekblom, 1979; Grose, 1958; Holewijn & Heus, 1992; Johnson & Leider, 1977; Kwon et al., 2013), while also exerting an important anti-fatigue effect (Bacon et al., 2012; Clarke et al., 1958; Edwards et al., 1972; Galoza et al., 2011; Holewijn & Heus, 1992; Kwon et al., 2013; Lind, 1959; Verducci, 2000). For example, early studies report ~11-to-21% decrease in maximal strength following limb cold water immersion (10-15°C for 8-30 min) (Grose, 1958; Johnson & Leider, 1977) whereas application of ice or cold packs to exercising muscle has been shown to increase the volume of work completed by ~15-26% (Bacon et al., 2012; Galoza et al., 2011; Thornley et al., 2003; Verducci, 2000). While it is becoming accepted that local cold exposure may improve fatigue-resistance, mechanistic underpinnings remain unclear. Current explanations include greater local muscle reflexes and excitability, altered motor unit recruitment patterns, increased neurotransmitter signaling, local analgesic effect, and/or reduction in perceived effort (Hopkins et al., 2002; Kwon et al., 2010; Palmieri-Smith et al., 2007; Prentice, 1982; Racinais & Oksa, 2010). Given the highly exothermic nature of metabolic reactions, it is also possible that precooling aids the maintenance of temperature homeostasis in muscle, thereby averting other molecular mechanisms that induce fatigue (e.g., acidosis, Ca^{2+} handling, etc) (Cheng et al., 2018).

Compared to application of cold to skeletal muscle, much less is known about the effects of acute heat stress on strength and fatigue (Latella et al., 2019). Studies that have evaluated direct, local application of heat to skeletal muscle generally show no effect (Holewijn & Heus, 1992; Long & Hopkins, 2009; Thornley et al., 2003) or an increase (Mallette et al., 2021) in peak force or torque. Interestingly, heat applied to a working limb reduces discomfort, thereby increasing exercise tolerance (Stadnyk et al., 2018). Furthermore, heat augments motor unit recruitment patterns, which is suspected to contribute to enhanced muscle performance (Mallette et al., 2021) and heat applied 1 d prior to RE enhances recovery (Nosaka et al., 2006). While applying heat may increase muscle strength, it also reduces fatigue resistance (Holewijn & Heus, 1992; Sargeant, 1987; Thornley et al., 2003). Central temperature is believed to govern neural drive to muscle (Racinais & Oksa, 2010). Therefore, local heating may exert its effects on muscle performance via peripheral mechanisms (e.g., ion channel behavior, depolarization patterns, etc.).

In general, when recovery is carefully considered, the volume of resistance exercise performed during training is directly related to the magnitude of adaptation. Therefore, identifying practical approaches to enhance training volume are of interest. Given the previously reported benefits of independent heat and cold exposure to exercising muscle, our intention was to explore alternated local heating and cooling in combination with isometric exercise training. We hypothesized that this form of thermal stress prior to exercise training sessions would lead to improved size and performance. Coupled with the practicality and feasibility of the intervention employed here, improving size and performance in such a short time frame may have therapeutic and ergogenic aid implications.

Methods

General overview

Twelve healthy college-aged males (*N*=8) and females (*N*=4) participated in this study. Participants were recruited from the greater Chico, CA area by personal interaction. All participants were screened based on ACSM guidelines (Riebe, 2018). Medical health history and physical activity readiness (PARQ) questionnaires were completed to determine eligibility. Participants with prior skeletal muscle injuries, inflammatory diseases, participation in formal exercise training, or heating/cooling treatment in the prior 6 months were excluded. The study was approved by the Institutional Review Board at California State University, Chico (#28089) and followed Helsinki Declaration ethic guidelines for human research of 1975 which was later updated at the World Medical Assembly in Fortaleza. All study procedures, risks, and benefits were explained to participants before they gave written consent to participate.

Experimental protocol

This is a randomized contralateral limb-controlled study based on work by Stadnyk et al (Stadnyk et al., 2017). The intervention utilized here consisted of 4-wk control and exercise training conditions (Figure 1).

Each participant's dominant arm served as the control (no exercise and no heating/cooling) while the contralateral arm participated in the exercise training program (exercise + heating/cooling). Anthropometric and pre- and post-intervention size and performance assessments were conducted in the control and contralateral arms.

Pre- and post-intervention assessments

Participant age, height, weight, BMI, resting HR, and resting BP was determined before and after the intervention. Size is reported here as fat-free cross-sectional area (FFCSA) of the forearm and upper arm and was calculated to estimate lean mass (Aghazadeh et al., 1993; Bishop et al., 1987). The equation utilized to determine FFSCA was:

Equation 1. $$\mathrm{FFCSA} = \pi[(c/\pi) - (\mathrm{SKF}/2)/2]^2$$

In equation 1, c refers to limb circumference, SKF is skinfold measurement at the designated site, and π is the constant 3.14159. The largest limb circumference was recorded to represent c for the upper arm (between olecranon and acromion process) and forearm (between olecranon process and distal radioulnar joint). SKF was assessed at the triceps (vertical fold on the posterior midline, midway between the acromion and olecranon processes) for the upper arm and midway between the olecranon process and distal radioulnar joint on the lateral side for the forearm. SKF measures were taken via Lange skinfold calipers (Beta Technology, Santa Cruz, CA, USA) on the right side of the participants body in the resting position (i.e., arm resting at side) in triplicate with mean values recorded.

Figure 1

General Study Overview

Pre	4-Week Intervention	Post
Upper arm - Size - Performance **Forearm** - Size - Performance	**Exercise** **- Random order of heating/cooling prior to all exercise** - Forearm: 1 set isometric exercise @60% MVC until exhaustion *>2 h break* - Upper arm: 1 set isometric exercise @60% 1RM until exhaustion **Control** **- No heating/cooling** - No exercise	**Upper arm** - Size - Performance **Forearm** - Size - Performance

Notes. General study overview. Briefly, pre- and post-intervention size and performance assessments were conducted in the control and contralateral arms. See Methods for more detailed information.

Performance was evaluated in two ways, maximal strength (i.e., upper arm 1RM and forearm MVC) and time to fatigue (i.e., upper arm and forearm sustained isometric exercise). 1RM was determined via unilateral dumbbell curl in the seated position, with feet flat on the floor, and included an initial self-selected dynamic warmup followed by a progressive increase in weight until failure (brief rest between completed repetitions; ~2 min). A successful repetition was determined when the dumbbell was raised in a controlled fashion from the resting 180° position to full flexion of the biceps (dumbbell approaching glenohumeral joint). A brief period of rest (~2 min) was permitted between 1RM determination of each arm. MVC was reported as the maximum amount of force developed during 3 attempts via unilateral Jamar hydraulic dynamometer (J.A. Preston Corp., Clifton, NJ, USA) handgrip exercise. Each MVC attempt was completed in the seated position, feet flat on the floor, with the arm completing the exercise in a 90° joint angle (~2 min rest between attempts). Before the initial attempt, handle position was adjusted to ensure good fit with the participant's hand. Upper arm fatigue was evaluated via unilateral, isometric/static dumbbell curl at 60% 1RM. Testing was performed in the seated position, feet flat on the floor, with the arm completing the exercise maintained at a 90° joint angle. Time to fatigue was noted when the arm performing the exercise failed to maintain a 90° elbow joint angle. Forearm fatigue was assessed via unilateral, isometric handgrip exercise at 60% MVC. Testing was performed in the seated position, feet flat on the floor, with the arm completing the exercise maintained at a 90° joint angle. Time to fatigue was noted when the arm performing the exercise failed to maintain 60% MVC (i.e., failed to maintain prescribed tension on the handgrip dynamometer). At least 15 min rest separated upper arm and forearm fatigue testing.

Exercise training program

Exercise training was only completed by the non-dominant exercise arm (control arm did not exercise). Exercise was performed 3x/week with at least 24 h rest between training sessions. Each training session consisted of 1 set to fatigue at 60% 1RM (upper arm) and 1 set to fatigue at 60% MVC (forearm) separated by at least 2 h. Each set completed (upper arm and forearm) during training was preceded by a randomized order of heating (40°C, 15 min) and cooling (12°C, 15 min). Heating and cooling was applied via a temperature controlled gel pack with adjustable strap. Temperature of the gel pack was adjusted via microwave (heating) and overnight cold freezer storage (cooling). Gel packs were applied to the upper arm/forearm when the appropriate temperature was reached.

Statistical analyses

Data were analyzed via SPSS v. 28.0 (IBM SPSS, Chicago, IL, USA). A paired t-test was performed to compare pre- and post-intervention anthropometric characteristics. A two-way ANOVA (condition x time) with repeated measurement was utilized to evaluate size and performance in response to the intervention in the control and exercise arms. Pearson correlation coefficient was completed to explore potential relationships among participant characteristics and main outcomes (size and performance metrics). Data are reported as mean ± SE. Significance was set at $p < 0.05$.

Results

General participant characteristics are presented in Table 1. Given the short duration of this intervention, no differences to age, height, weight, or BMI were noted ($p > 0.05$). However, resting HR increased 10% following the 4-wk intervention period ($p < 0.05$).

Table 1

General participant characteristics.

Time	Age (y)	Height (cm)	Weight (kg)	BMI (kg/m^2)	Resting HR (bpm)	Resting SBP (mmHg)	Resting DBP (mmHg)
Pre (n=12)	21 ± 1	173 ± 2	70 ± 2	24 ± 1	68 ± 2	114 ± 3	68 ± 2
Post (n=12)	21 ± 1	174 ± 3	71 ± 3	24 ± 1	74 ± 3*	116 ± 3	71 ± 4

Notes. Values are mean ± SE; n, number of participants; y, year; cm, centimeters; kg, kilograms; m, meter; bpm, beats per minute; mmHg, millimeters of mercury; HR, heart rate; BMI, body mass index; SBP, systolic blood pressure; DBP, diastolic blood pressure *$p < 0.05$.

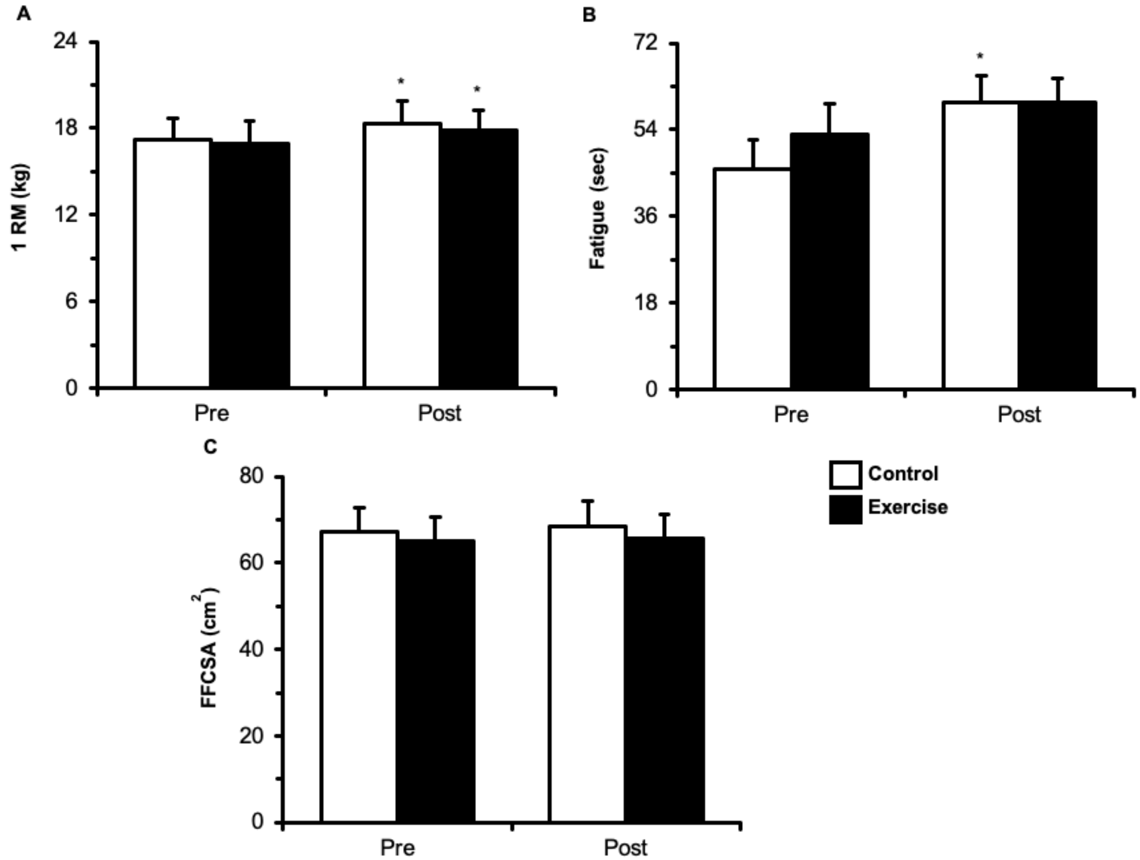
Upper arm

Performance. Maximal biceps 1RM strength (Figure 2A) increased significantly ($p < 0.05$) in the exercise trained (+6%) and control arms (+7%). While the exercise trained arm increased time to fatigue (+25%; Figure 2B) this change did not reach statistical significance ($p > 0.05$). The control arm did realize an increase (+40%; $p < 0.05$) in time to fatigue in response to the intervention period.

Cross-sectional area. No change ($p > 0.05$) in fat-free cross-sectional area (Figure 2C) of the upper arm was noted after the intervention.

Figure 2

Upper Arm Size and Performance



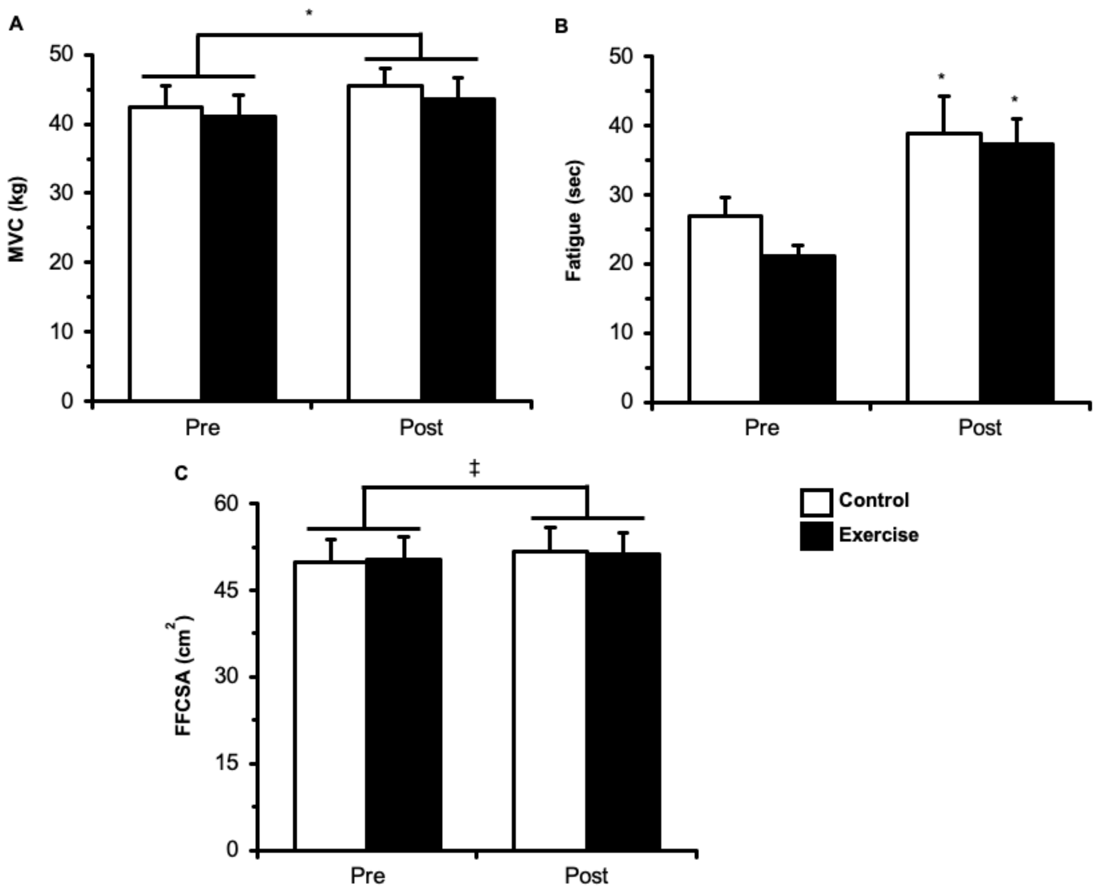
Notes. A) 1-repetition maximum (1RM), B) time to fatigue, and C) fat-free cross-sectional area (FFCSA) of the upper arm before and after the 4-wk intervention period. See *Exercise training program in Methods*). *$p < 0.05$ vs Pre.

Forearm

Performance. The intervention did not affect MVC in the exercised trained or control arm ($p > 0.05$; Figure 3A). However, an effect of time was noted for MVC, where both groups combined increased handgrip strength 8% ($p < 0.05$). Time to fatigue (Figure 3B) increased significantly in the exercise trained (+82%) and control arms (64%).

Figure 3

Forearm Size and Performance



Notes. A) Maximum voluntary contraction (MVC), B) time to fatigue, and C) fat-free cross-sectional area (FFCSA) of the forearm before and after the 4-wk intervention period. See *Exercise training program in Methods*). *$p < 0.05$ vs Pre. ‡$p < .10$ vs Pre.

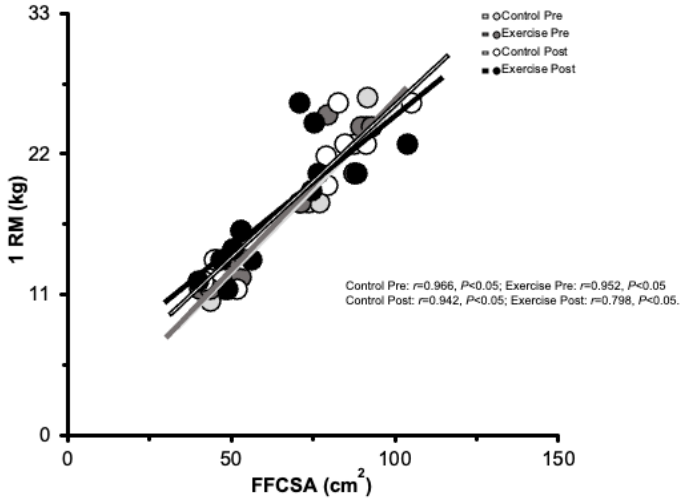
C*ross-sectional area.* Fat-free cross-sectional area (Figure 3C) of the forearm did not change ($p > 0.05$) in the exercise trained or control arms in response to the intervention. However, a trend toward an effect of time was noted, where both groups combined increased FFCSA 3% ($p < .10$).

Select relationships

Many notable relationships between performance and size were observed before and after the intervention period. As anticipated, upper arm 1RM was closely related to FFCSA in the control and exercise arms before and after the intervention (Figure 4; r = 0.798 to 0.966, $p < .10$ to $p < 0.05$). Interestingly, the relationship between forearm MVC and FFCSA appeared to increase in the control (Pre: $r = 0.537$, $p < .10$; Post: $r = 0.865$, $p < 0.05$) and exercise (Pre: $r = 0.691$, $p < 0.05$; Post: $r = 0.879$, $p < 0.05$) arms in response to the intervention. Time to fatigue in the forearm was related to FFCSA before the intervention ($r = 0.55$, $p < 0.05$) in the control arm, but not after ($r = -0.185$, $p > 0.05$). Similarly, time to fatigue in the upper arm was related to FFCSA before the intervention ($r = 0.578$, $p < 0.05$) in the exercise arm, but not after ($r = -0.003$, $p > 0.05$).

Figure 4

Forearm Size and Performance



Notes. Association between 1-repetition maximum (1RM) and fat-free cross-sectional area (FFCSA) of the upper arm before and after the 4-wk intervention period.

Discussion

The overarching purpose of this study was to explore alternated local heating and cooling in combination with isometric resistance exercise training. Identifying novel, practical exercise interventions are important as they have implications for enhancing performance and rehabilitation. The heating and cooling strategy employed here was selected for several reasons, including 1) the suspected effects of these stresses on improving strength and fatigue resistance, 2) feasability regarding economics and necessary expertise, and 3) unexplored nature of combined heat/cold stress. Overall, our approach was to employ practical methology that maximizes training quality and translation into clincial settings. Contrary to our original hypothesis, there did not appear to be a clear benefit of alternating heat and cold stress prior to training sessions. Principle findings show increased maximal strength of the upper arm and forearm (both groups), fatigue resistance of the upper arm (control only) and forearm (both groups), and FFSCA of the forearm (both groups).

Based on studies that demonstrate cold-induced reductions in strength, it is estimated that maximal strength declines ~3% per 1°C decrease in muscle temperature (Bergh & Ekblom, 1979; Holewijn & Heus, 1992; Sargeant, 1987). Interestingly, one of the original investigations on local cold exposure noted an immediate decrease in maximal strength that persisted until ~40 min postexercise and then increased ~20% above pretreatment levels; demonstrating the importance of timing (Johnson & Leider, 1977). In general, studies show no effect (Holewijn & Heus, 1992; Long & Hopkins, 2009; Thornley et al., 2003) or an increases (Mallette et al., 2021) in strength following local heat stress. One possible explanation for this heat-induced increase in strength is due to altered motor unit recruitment patterns, leading to enhanced neural drive (Mallette et al., 2021). While maximal strength appears to decline acutely, local cold stress also exerts an anti-fatigue effect with the optimal muscle temperature reported as being ~26°C (Edwards et al., 1972). A direct relationship (*r* -0.98) has been found between temperature and fatigue resistance during isometric exercise after pre-exercise direct application of thermal stress (-11.9-to-48°C) (Thornley et al., 2003). Furthermore, application of ice or cold packs to exercising muscle has been shown to increase the volume of work completed by ~15-26% (Bacon et al., 2012; Galoza et al., 2011; Thornley et al., 2003;

Verducci, 2000). Therefore, modulating muscle temperature has meaningful implications for training quality.

While several studies have explored the effects of heat or cold stress alone on skeletal muscle (Hyldahl et al., 2020), to our knowledge, none exist that incorporated a combined strategy as was utilized here. More specifically, existing studies typically implement heating or cooling in the postexercise period during training. Here we show that the exercising arm with alternating heating/cooling increased biceps 1RM and forearm MVC. Though cooling was applied in the postexercise period (20 min arm cold water immersion at 10°C), Yamane et al (Yamane et al., 2006) reported similar improvements in forearm isometric strength following 4-wk training at ~75% MVC. While not all studies agree (Hyldahl et al., 2020), others also report improved performance when incorporating postexercise cooling with RE training, including 35% greater dynamic strength, but not isometric, following 12-wk RE with limb immersion in cold water (10 min at 10°C) (Roberts et al., 2015). Compared to effects of cold, much less is known about heat and adaptability to RE. This is surprising given Gato et al. (Yamashita-Goto et al., 2002) demonstrated greater stretch-induced hypertrophy of L6 myotubes when passively heated compared to a “stretch-only” group nearly 2 decades ago. The few investigations that have attempted to translate these pre-clinical findings into humans show increased muscle size and isometric strength with passive heating (8 h/d, 4 d/wk for 10wk at an increased muscle temperature of ~2°C) (Goto et al., 2011) and increased isometric muscle strength (but not size) after passive heating (90 min/d, 5 d/wk for 8 wk at ~52°C) (Kim et al., 2020). While RE studies utilizing heat are sparse, two recent reports show that local heat application prior to RE training sessions(3 d/wk for 6 wk; 20 min at 75 °C) (Nakamura et al., 2019) and during/after RE training sessions (2-3 d/wk for 12 wk; limb heated to ~38°C) (Stadnyk et al., 2017) increased muscle strength and size.

Although the control arm was not directly involved in the isometric exercise training and heating and cooling stimulation, it clearly adapted as indicated by increasing upper arm strength and fatigue resistance, forearm MVC, fatigue resistance, and size. Observations such as those noted here in the control arm have been made dating back to 1894 (Scripture et al., 1894) and are generally termed “cross-education”. This adaptation in a non-exercising, contralateral limb is suspected to occur via the central nervous system. Not all studies demonstrate this effect (Tesch & Karlsson, 1984), however, it has become well-accepted and our findings provide additional support (Kannus et al., 1992).

It is important to acknowledge this study is not without limitations. First, we did not include an exercise or heat/cold stress only group. While the purpose of this study was to determine if direct heat and cold combined application with exercise training resulted in improved size and performance, the approach utilized here makes it difficult to extrapolate findings to benefits beyond exercise alone. Second, we selected to assess potential changes in muscle size indirectly (i.e., FFCSA). Therefore, we can only speculate as to changes in FFCSA being due to increases in skeletal muscle size specifically. Lastly, we did not directly measure muscle temperature. It has been established that muscle temperature changes of ~1-2°C greatly impacts performance. Though a similar heat and cold application strategy was implimented here in studies that do direclty assess changes in muscle temperature, it is not possible to confirm muscle temperature was altered.

Exercise training quality is a primary factor governing adaptations to size, strength, and fatigue resistance. Therefore, identifying practical methods to optimize training strategies have implications for performance and rehabilitation. With guidance from reports on the benefits of independent heat and cold exposure to exercising muscle, our intention was to explore a novel, practical exercise training paradigm that incorporated both forms of thermal stress. Though increased performance was observed, we did not find an apparent benefit of the local heat and cold application model utilized here. Given the unexplored nature of this area, findings provided here will begin to lay the framework for future work. These studies are encouraged to examine the potential effects of timing and order of heat/cold application.

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***Address correspondence to**:
Feng He, Ph.D.
Department of Kinesiology
California State University, Chico
Chico, CA
Email: fhe@csuchico.edu

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