Palm Cooling Delays Fatigue during High-Intensity Bench Press Exercise

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[1]Department of Health, Exercise & Sports Sciences, University of New Mexico, Albuquerque, NM; [2]School of Biomedical and Health Science, University of Western Sydney, Sydney, AUSTRALIA; and [3]Department of Orthopaedics and Rehabilitation, University of New Mexico School of Medicine, Albuquerque, NM

ABSTRACT

KWON, Y. S., R. A. ROBERGS, L. R. KRAVITZ, B. A. GURNEY, C. M. MERMIER, and S. M. SCHNEIDER. Palm Cooling Delays Fatigue during High-Intensity Bench Press Exercise. *Med. Sci. Sports Exerc.*, Vol. 42, No. 8, pp. 1557–1565, 2010. Local cooling can induce an ergogenic effect during a short-term intense exercise. One proposed method of personal cooling involves heat extraction from the palm. **Purpose**: In this study, we hypothesized that local palm cooling (PC) during rest intervals between progressive weight training sets will increase total repetitions and exercise volume in resistance-trained subjects exercising in a thermoneutral (TN) environment. **Methods**: Sixteen male subjects (mean ± SD; age = 26 ± 6 yr, height = 178 ± 7 cm, body mass = 81.5 ± 11.3 kg, one-repetition maximum (1RM) bench press = 123.5 ± 12.6 kg, weight training experience = 10 ± 6 yr) performed four sets of 85% 1RM bench press exercise to fatigue, with 3-min rest intervals. Exercise trials were performed in a counterbalanced order for 3 d, separated by at least 3 d: TN, palm heating (PH), and PC. Heating and cooling were applied by placing the hand in a device called the rapid thermal exchanger, set to 45°C for heating or 10°C for cooling. This device heats or cools the palm while negative pressure (−35 to −45 mm Hg) is applied around the hand. **Results**: Total exercise volume during the four PC sets (2480 ± 636 kg) was significantly higher than that during TN (1972 ± 632 kg) and PH sets (2156 ± 668 kg, $P < 0.01$). The RMS of the surface EMG with PC exercise was higher ($P < 0.01$), whereas esophageal temperature ($P < 0.05$) and RPE ($P < 0.05$) were lower during PC compared with TN and PH. **Conclusions**: PC from 35°C to 20°C temporarily overrides fatigue mechanism(s) during intense intermittent resistance exercise. The mechanisms for this ergogenic function remain unknown. **Key Words:** ESOPHAGEAL TEMPERATURE, EMG, EXERCISE TRAINING, RESISTANCE EXERCISE

Traditionally, local cooling has been used in a rehabilitation situation or between bouts of intense exercise to reduce swelling and inflammation (22). However, recently, it has been shown that specific applications of local cooling can produce an ergogenic effect in athletes during short and intense resistive exercise (4,37). Verducci (37) suggested that one possible way to decrease muscular fatigue and to increase the weight lifted during weight training is to apply cooling to the skin over the exercising muscle during rest periods between sets. However, previous research of the effects of local cooling on muscle function during exercise has produced inconsistent findings, which are likely due to the different locations and strategies for cooling such as cold or ice water baths, gel packs, or plastic bags with ice cubes and periods of cooling from 10 to 45 min over the muscle of interest or body regions (5,9,16,18,25,33).

In contrast to direct external muscle cooling, as performed by each of Verducci (37,38), Hopkins et al. (17) and Palmieri-Smith et al. (29) applied cooling to a joint close to the exercising muscle and found increased local muscle reflexes, muscle excitability, and short-term release of neurotransmitters from the CNS. These phenomena suggested that local cooling of the periphery that does not involve active muscles may enhance motor neuron output of the active muscles as detected from surface electrode EMG. Such findings raise the possibility for the importance of CNS processing of peripheral afferent stimulation or direct central effects of cooling on exercise performance.

This investigation was undertaken to determine whether there are significant differences in muscle fatigue and EMG activity as well as subjective perceptions of fatigue when trained subjects perform sets of high-intensity isotonic exercise (bench press) with cooling applied to the hands during rest intervals between sets. We hypothesized that total work volume during multiple sets of high-intensity bench press exercise will be increased by cooling compared with local heating or thermoneutral (TN) conditions. We also hypothesized that HR and the subjective perception of fatigue would be reduced during cooling compared with

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the TN and palm heating (PH) conditions. Finally, documenting improved capacity for resistance exercise through neural manipulation would add to the growing body of research evidence for the importance of central processing of neurological input signals during short-term high-intensity exercise performance (35,36).

METHODS

Subjects

Sixteen healthy male subjects volunteered for this study. The subjects had participated in regular, intense weight training for a minimum of 5 yr, and their ratio of weight pressed to body weight during bench press was more than 80% of age-based upper body strength (1). The protocol for this study was approved by the University of New Mexico Human Research Review Committee, and all subjects provided informed, written consent before participation. Subjects were screened for cardiovascular and musculoskeletal diseases using a medical history questionnaire, an activity questionnaire, and the Physical Activity Readiness Questionnaire. Subjects were also screened for body composition to improve signal detection from surface EMG. After the initial screening, body density was determined using the sum of three skinfold sites and the Jackson and Pollock equations; ethnic and gender-specific equations were used to calculate the percentage of body fat from body density (20). Subjects were excluded from the study if they had more than two positive cardiovascular risk factors as outlined by the American College of Sports Medicine (1), had high blood pressure (>140/90 mm Hg), were taking ergogenic supplements that could affect exercise performance, or had body fat >20%. Subjects were instructed not to exercise the day before a trial, to refrain from caffeine ingestion (coffee or tea) the morning of each trial, to otherwise follow their normal diet, and to eat a light meal 2 h before coming to the laboratory.

Overall Protocol

There were a total of four experimental days. During the first testing day, subjects were familiarized with the testing protocol. They performed a one-repetition maximum (1RM) supine bench press test, and after 5 min of rest, they completed one endurance set to fatigue at 85% of 1RM. Before the first 1RM test, each subject gained familiarity with the barbell bench press exercise by performing it under the guidance of the primary investigator. Subjects were trained to perform each concentric and eccentric phase of the bench press through a fixed range of motion and at a rate of 2 s up and 2 s down in time. During the other 3 d, they performed the same 1RM and one set of 85% 1RM as performed during the first day, but they then also performed three additional endurance sets at 85% of 1RM. During the rest period between sets 2 and 4, the hand was exposed to either 1) TN with negative pressure, 2) local palm cooling (PC) with negative pressure, or 3) local PH with negative pressure (Fig. 1). A counterbalanced design was used to minimize any learning or order effects. All tests were done at the same time of day for each subject. All testing took place at an altitude of 1572 m (barometric pressure = 635 mm Hg) in the northern hemisphere in the months of April through May.

Procedures during Each Testing Day

Treatment conditions. Hand cooling and heating with negative pressure were induced by using two rapid thermal exchanger (RTX) hand cooling devices, one on each hand (RTX Heating/Cooling Model No. 200962-006B; AVAcore, Inc., Palo Alto, CA). The RTX consists of a metallic cone heat exchanger surface on which the palm of the hand is placed and a plastic chamber that encloses the hand. A seal above the wrist maintains a vacuum around the hand. Air is pumped from the device, and negative pressure can be controlled and maintained. The circulating water temperature was maintained at 10°C during the cooling trials and at 45°C during the heating trials, and negative pressure was maintained at 45 mm Hg. The 10°C temperature was chosen based on previous research of hand immersion showing that this temperature is optimal and causes limited vasoconstriction in the hand. For cooling and heating trials, the hand was cooled or heated for 2.5 min during each rest period after the first 85% of 1RM set. The control trials consisted of placing the hand in the RTX with negative pressure but without application of cold or hot water.

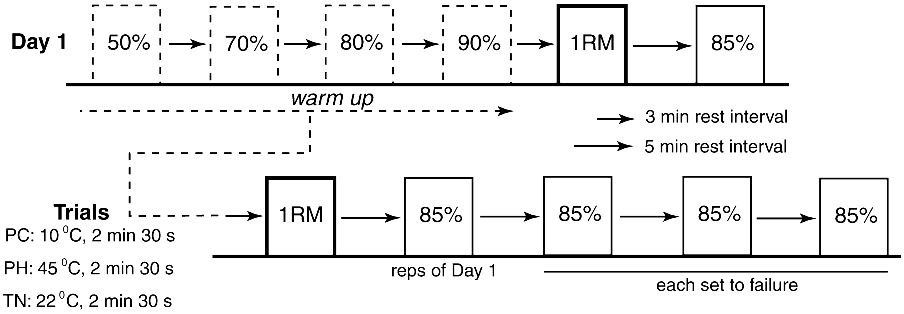

FIGURE 1—Protocols for warm-up, 1RM test, and 85% of 1RM sets of bench press exercise in TN, PC, and PH conditions. Exercise intensity (% of 1RM) is denoted in each *column* representing each set. After 1RM and the first set, the exercise in three sets of every protocol continued until the subjects failed to complete a lift.

Exercise Procedures

Day 1: 1RM and one 85% of 1RM endurance test. On the testing day, participants were asked if they had any soreness or injury to their shoulders, triceps, and chest and if they had refrained from caffeine and vigorous exercise in the previous 24 h. If subjects complied to these requirements, they did their usual warm-up and then positioned themselves under the bar with their usual grip. The positions of the minimus fingers of each hand were marked on the bar to ensure the same grip distance on the bar during all tests. The type of grip used (closed or open) was self-chosen. Supine bench press strength was assessed by measuring the 1RM, and after 5 min, an 85% of 1RM endurance test was performed. The 1RM bench press was determined according to the methods described by Doan et al. (8). Subjects were required to perform a warm-up of 10 repetitions at 50% of (predicted) 1RM, 5 repetitions at 70% of 1RM, 3 repetitions at 80% of 1RM, and 1 repetition at 90% of 1RM, followed by three attempts to determine the subject's actual 1RM. All subjects were given 3 min of rest between sets. After the 1RM test, subjects had a 5-min rest period and then tried to lift as many repetitions as possible using 85% of 1RM. A 1RM test was performed before each fatigue test because the EMG signal from the muscle surface varies from one location to another, and thus, the absolute EMG signal cannot be compared between separate days.

Days 2, 3, and 4: 1RM and four 85% 1RM endurance tests. The participants were required to perform a warm-up of 10 repetitions at 50% of 1RM, 5 repetitions at 70% of 1RM, 3 repetitions at 80%, and 1 repetition at 90% of 1RM, stretching chest, shoulder, and triceps between sets. After 5 min, they lifted their 1RM. After another 5 min of rest, four sets with weights of 85% of 1RM were performed until fatigue. Between each set, they rested for 3 min. The 3-min rest periods between sets 2, 3, and 4 consisted of a 15-s transition from the exercise to the treatments, 2 min 30 s of PC (10°C), PH (45°C), or a TN trial with negative pressure and another 15-s transition from the rest period to the next set. EMG measurements were obtained throughout the 1RM and four endurance tests (Fig. 1).

Specific Measurements

RPE. Immediately after each endurance set, participants were asked to answer the question, "How hard was your workout?" to find their perceived exertion after the completion of each set on the basis of a modified 10-point RPE scale (0, rest; 10, maximal) (7).

Esophageal and palm temperatures. Uncovered skin thermistors (Grant Instruments Ltd., Cambridge, UK) were attached to the right palm with elastic straps during the TN condition. During PC and PH conditions, palm temperature was measured by the RTX (by thermocouples embedded in the hand cone). In each condition, palm temperatures (T_{pa}) were recorded during 2.5 min of the rest periods. A subgroup of subjects ($n = 6$) inserted a calibrated esophageal thermistor (YSI Precision 4400 Series, Yellow Springs, Inc., Yellow Springs, OH) through their nose and into the esophagus. The thermistor was inserted to one-fourths of the subject's height, and the depth was adjusted ±1 in to obtain the highest reading. All thermistors were connected to a data logger (Squirrel; Grant Instruments Ltd.), which recorded esophageal temperature (T_{es}) during all three conditions and palm temperature during the TN condition every 5 s. Palm temperature during PC and PH conditions was obtained from the RTX and was recorded manually every 15 s.

EMG. Gel electrodes were placed on the belly of the following muscles on the left side of the body aligned parallel to the muscle fibers: the sternal head of the pectoralis major (PM), the anterior deltoid (AD), the long head of the triceps brachii (LT), the lateral head of the triceps (LTT) brachii, and on the styloid process of ulna as a ground. Always, the line between two electrodes was parallel to the muscle's line of pull. The electrode sites were prepared by shaving, abrasion with sandpaper, and swabbing with alcohol pads to lower skin resistance. Each electrode was secured by an adhesive tape. The electrode sites were marked using an anatomical pen on the skin to ensure that the same site was used on different days. Muscle EMG voltage signals were acquired at a rate of 1500 Hz (MyoSystem 1200; Noraxon, Inc., Scottsdale, AZ), diverted to an analog signal acquisition system through a 68-pin junction box (CA1000 unit; National Instruments, Austin, TX), connected in series to a data acquisition card (National Instruments), and collected using custom-written software (LabVIEW; National Instruments). To aid in postcollection signal processing, an electronic goniometer (Biopac Systems, Santa Barbara, CA) was attached to the elbow to provide a signal at 1500 Hz to monitor changes in elbow flexion and extension. No filters were applied to raw EMG data.

Raw EMG signal processing was completed after collection using a custom-written software that provided objective automated analyses that did not require independent interpretation by the researchers (LabVIEW; National Instruments). The program involved isolation of EMG signals from the PM, AD, LT, and LTT during every muscle contraction on the basis of the goniometer signal. The concentric and eccentric movement from each contraction was also differentiated on the basis of the goniometric signal. The root mean square (RMS) and spectrum analysis for frequency domain, mean frequency (MF), and median frequency (MDF) for each contraction were then calculated on the basis of a signal iteration procedure where the time difference between each signal spike was computed and converted to frequency, and the total iterative frequencies was summed and computed as mean and median frequencies. The electrical manifestations of muscle activity and muscle fatigue were investigated by tracking the variation of the instantaneous RMS and MF and MDF of the surface EMG signals during the 1RM and the first contraction of the first set of 85% 1RM and the last contraction of the fourth set of 85% of 1RM.

Power analysis. The number of subjects was based on a power analysis using data from Verducci (37). Without cooling, mean ± SD total work was 52,795 ± 7424 J, whereas with cooling, the mean ± SD total work was 60,233 ± 8223 J. Using the SD from Verducci's data, approximately 16 subjects would be sufficient to detect a significant difference in mean total work between hand cooling and no cooling ($\alpha = 0.05$ and a power of 0.8). Therefore, we recruited 16 healthy, resistance-trained male subjects for this study.

Statistical Analyses

All statistical computations were performed using STATISTICA version 7.1 software (StatSoft, Inc., Tulsa, OK). A two-way repeated-measures ANOVA test was used to quantify the differences in HR, T_{es}, T_{pa}, and RPE between conditions (TN, PC, and PH) and the four sets. Exercise volumes (kg; sets × repetitions × weight) among conditions were compared using a one-way repeated-measures ANOVA. When a significant F-ratio was obtained, Tukey honestly significant difference test was performed. Statistical significance was accepted at $P < 0.05$. All data are presented as mean ± SD.

RESULTS

Subject characteristics and environmental variables. Descriptive characteristics of the 16 healthy male subjects who participated in the study are as follows: age = 26 ± 6 yr, height = 178 ± 7 cm, weight = 81.5 ± 11.3 kg, body fat = 10.3% ± 5.4%, 1RM = 123.5 ± 12.6 kg, the ratio of weight pressed to body weight = 1.5 ± 0.2, and weight training experience = 10 ± 6 yr. There were no differences in ambient temperature (TN = 23.6°C ± 1.2°C, PH = 23.5°C ± 0.8°C, and PC = 23.5°C ± 0.9°C, $P = 0.99$), relative humidity (TN = 18% ± 9%, PH = 18% ± 9%, and PC = 18% ± 9%, $P = 0.98$), or barometric pressure (TN = 631 ± 3 mm Hg, PH = 632 ± 3 mm Hg, and PC = 631 ± 3 mm Hg, $P = 0.55$) during the three conditions.

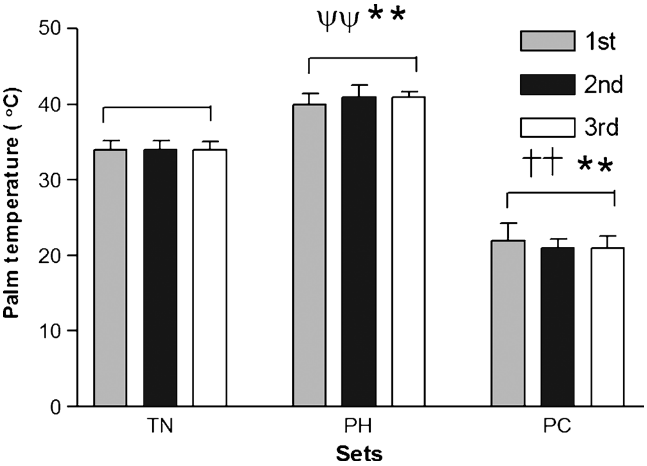

FIGURE 2—Mean palm skin temperature during the four 85% of 1RM sets of bench press exercise. Data were obtained during rest periods of TN, PC, and PH conditions. Each value represents the mean palm skin temperature ($n = 16$). Error bars indicate SD. Asterisk (*) indicates PC versus PH conditions (*$P < 0.05$, **$P < 0.01$). Symbol (†) indicates PC versus TN conditions (†$P < 0.01$, ††$P < 0.01$). Symbol (ψ) indicates PH versus TN conditions (ψ$P < 0.05$, ψψ$P < 0.01$).

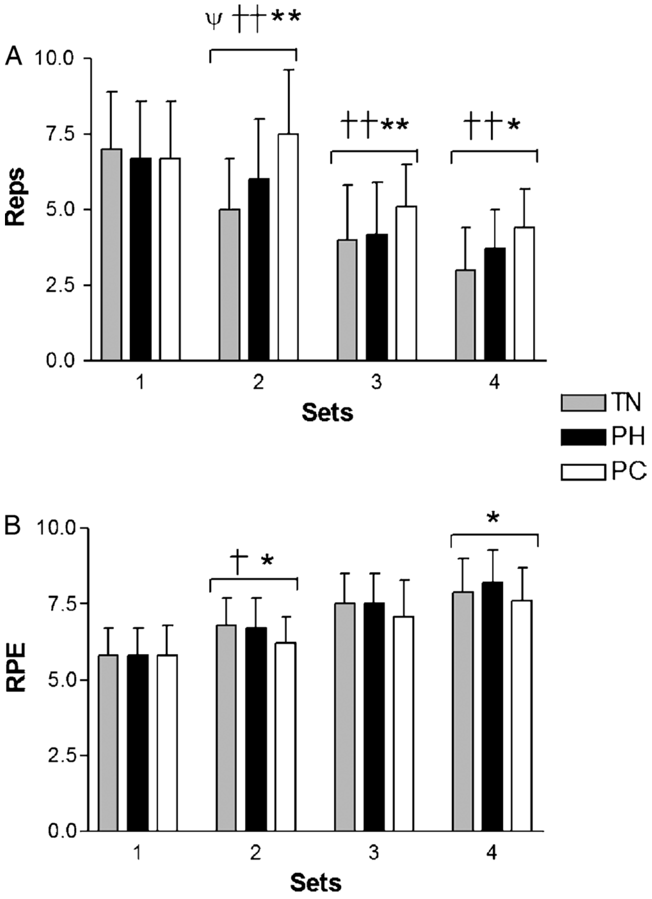

FIGURE 3—Repetitions (A) and RPE response (B) during the four 85% of 1RM sets of bench press test during TN, PC, and PH conditions. Each value represents the mean repetitions ($n = 16$). Error bars indicate SD. Asterisk (*) indicates PC versus PH conditions (*$P < 0.05$, **$P < 0.01$). Symbol (†) indicates PC versus TN conditions (†$P < 0.01$, ††$P < 0.01$). Symbol (ψ) indicates PH versus TN conditions (ψ$P < 0.05$, ψψ$P < 0.01$).

Mean palm skin temperature during rest periods among the three conditions. There were significant differences in palm skin temperature during rest periods between conditions ($P < 0.01$; Fig. 2). There were no significant differences within a condition between the three rest periods.

Repetitions. The number of repetitions to exhaustion per set decreased ($P < 0.01$) and varied among the conditions ($P < 0.01$; Fig. 3A). The PC (5.9 ± 2.1) condition had significantly higher mean repetitions than the TN (4.7 ± 2.2) and PH (5.1 ± 1.1) conditions. There was no significant difference in mean repetitions ($P = 0.06$) between TN and PH conditions. The condition × set interaction effect was significant ($P < 0.01$). In the PC condition, the second set had significantly higher ($P < 0.01$) repetitions (7.5 ± 2.1) than both the TN (5.1 ± 1.7) and the PH conditions (6.0 ± 2.0). The third set of the PC condition had significantly higher repetitions (5.1 ± 1.3) than the third set during the TN (3.6 ± 1.8, $P < 0.01$) and PH conditions (4.2 ± 1.7, $P < 0.01$), and the fourth set of the PC condition had higher repetitions (4.4 ± 1.3) than the TN (3.4 ± 1.4, $P < 0.01$) and PH conditions (3.7 ± 1.3, $P < 0.05$). In the PH condition, the second set had higher repetitions (6.0 ± 2.0) than the second set in the TN condition (5.1 ± 1.7, $P < 0.05$).

Exercise volume. There were significant differences in exercise volume among the TN, PH, and PC conditions. Mean exercise volume of PC (2479 ± 636 kg) was significantly higher than that of both PH (2156 ± 668 kg, $P < 0.01$) and TN (1972 ± 632 kg, $P < 0.01$). There was no significant difference between TN and PH in exercise volume ($P = 0.08$; Fig. 4A).

Core temperature in six subjects. Changes in T_{es} were significantly different among conditions ($P < 0.01$). The PC condition (36.97°C ± 0.08°C) had significantly lower mean T_{es} than both the PH (37.02°C ± 0.10°C, $P < 0.01$) and TN conditions (36.99°C ± 0.08°C, $P < 0.05$). There also was a significant time effect among baseline, rest periods, and 1 min after exercise after the fourth set ($P < 0.01$). The condition × set interaction effect was significant ($P < 0.01$; Fig. 5).

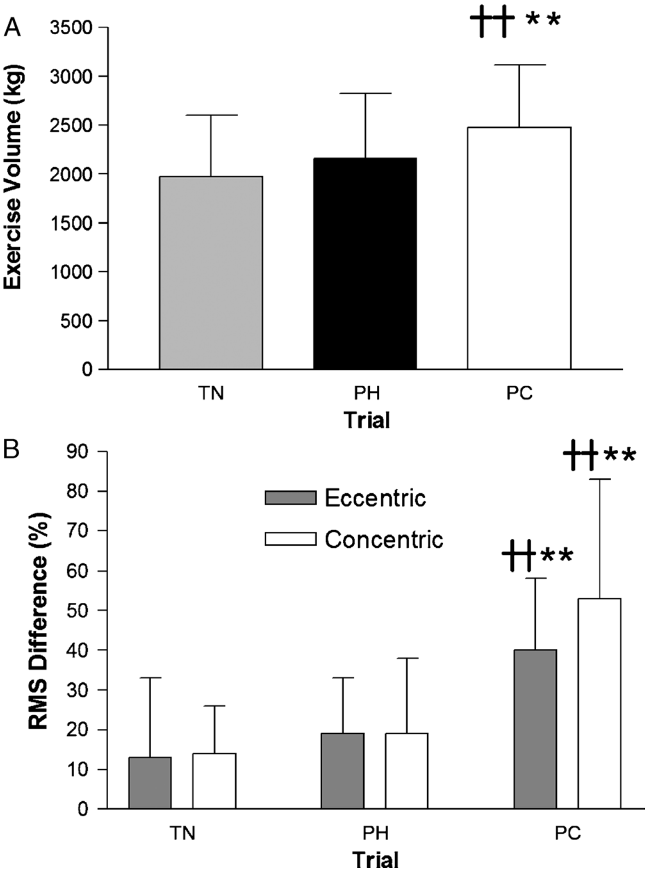

FIGURE 4—Total exercise volume (A) of the four 85% of 1RM sets of bench press and the mean difference (%) in RMS (B) during eccentric and concentric contractions from the LTT during the four 85% of 1RM sets of bench press testing during TN, PC, and PH conditions. Each value represents the mean value ($n = 16$). Error bars indicate SD. Asterisk (*) indicates PC versus PH conditions (*$P < 0.05$, **$P < 0.01$). Symbol (†) indicates PC versus TN conditions (†$P < 0.01$, ††$P < 0.01$). Symbol (ψ) indicates PH versus TN conditions ($\psi P < 0.05$, $\psi\psi P < 0.01$). CON, concentric; ECC, eccentric.

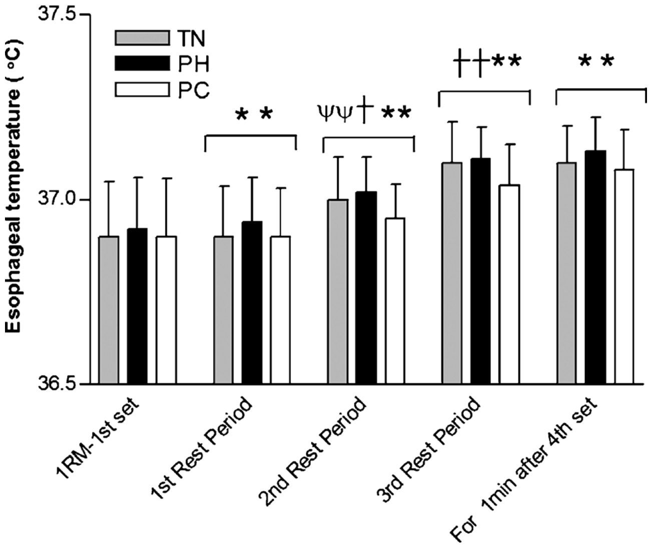

FIGURE 5—Esophageal temperature (T_{es}) during baseline, rest periods, and 1 min after the fourth set during the four 85% of 1RM sets of bench press test during TN, PC, and PH conditions. Each value represents the mean T_{es} ($n = 6$). Error bars indicate SD. Asterisk (*) indicates PC versus PH conditions (*$P < 0.05$, **$P < 0.01$). Symbol (†) indicates PC versus TN conditions (†$P < 0.01$, ††$P < 0.01$). Symbol (ψ) indicates PH versus TN conditions ($\psi P < 0.05$, $\psi\psi P < 0.01$).

RPE. Changes in RPE were significantly different among conditions ($P < 0.05$). The mean RPE during PC (6.7 ± 0.8) was significantly lower than that during PH (7.0 ± 1.1, $P < 0.05$). There were no differences between PC and TN (7.0 ± 1.2, $P = 0.08$) or between TN and PH conditions ($P = 0.87$). The RPE was significantly different between sets ($P < 0.001$; Fig. 3B). The condition × set interaction effect also was significant ($P < 0.05$). In the PC trial, the second set (6.2 ± 0.9) had significantly lower RPE than the TN (6.6 ± 2.5) and PH trials (6.7 ± 1.0, $P < 0.05$). In the PC trial, the fourth set (7.6 ± 1.1) had significantly lower RPE than the PH trial (8.2 ± 1.1, $P < 0.05$).

HR. Changes in HR were significantly different among the conditions ($P < 0.05$). The mean HR during TN trials (108 ± 26 bpm) was lower than that during PH trials (112 ± 26 bpm, $P < 0.05$). There were no differences in HR between TN and PC (108 ± 28 bpm) and between PH and PC trials ($P = 0.07$), and HR was different from baseline during the exercise and rest periods ($P < 0.01$; Fig. 6). The interaction effect was also significant ($P < 0.01$). During the second set, HR during PC (141 ± 19 bpm) was significantly higher than that during TN (135 ± 18 bpm, $P < 0.05$). During the rest period between the second and third sets, HR during PH (88 ± 21 bpm) was significantly higher than that during TN (86 ± 21 bpm, $P < 0.01$) and PC (83 ± 20 bpm, $P < 0.01$). During the rest period between the third

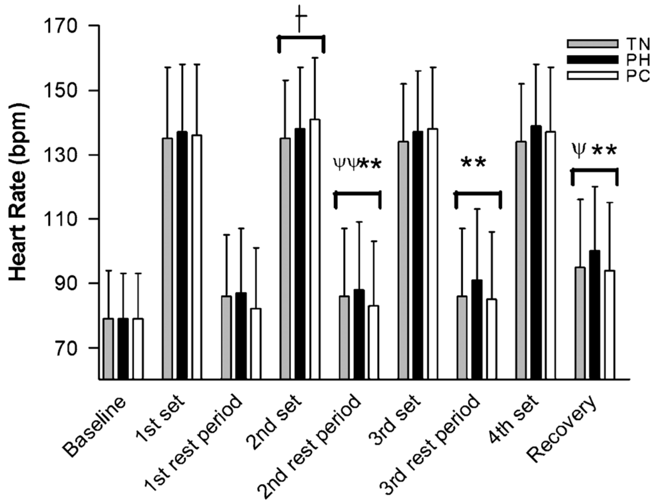

FIGURE 6—Mean HR during the four 85% of 1RM sets of bench press test during TN, PC, and PH conditions. Each value represents the mean HR (n = 16). Error bars indicate SD. Asterisk (*) indicates PC versus PH conditions (*$P < 0.05$, **$P < 0.01$). Symbol (†) indicates PC versus TN conditions (†$P < 0.01$, ††$P < 0.01$). Symbol (ψ) indicates PH versus TN conditions ($\psi P < 0.05$, $\psi\psi P < 0.01$).

and fourth sets, HR during PH (91 ± 21 bpm) was significantly higher than that during PC (86 ± 21 bpm, $P < 0.01$). During 1 min after exercise, HR during PH (100 ± 20 bpm) was significantly higher than during PC (94 ± 21 bpm, $P < 0.01$) and TN (95 ± 21 bpm, $P < 0.05$).

EMG. There were significant differences in EMG values during both eccentric and concentric movements only in the LTT (Table 1). The RMS (%) difference between the first repetition of the first set and the last repetition of the fourth set was significantly different among the TN, PH, and PC conditions. During eccentric movements, the RMS difference during PC (40% ± 18%) was significantly higher than that during both PH (19% ± 14%, $P < 0.01$) and TN conditions (12% ± 20%, $P < 0.01$). There was no significant difference between TN and PH in mean RMS difference (P = 0.06). For concentric movements, there were also significant differences in EMG RMS difference (%) from the first repetition of the first set to the last repetition of the fourth set among the TN, PH, and PC conditions ($P < 0.001$). The mean difference of PC (53% ± 30%) was significantly higher than both PH (37% ± 37%, $P < 0.001$) and TN (29% ± 29%, $P < 0.001$; as shown in Fig. 4B). There was no significant difference between TN and PH in mean difference (%). There were no significant differences in MF or MDF in any of the muscles during the eccentric or concentric contraction.

DISCUSSION

To our knowledge, this is the first study to assess the impact of mild PC and heating on fatigue during high-intensity multiset bench press exercise. The remarkable finding of this study was that an intervention on the basis of localized cold exposure distant from the exercised muscle mass enabled close to a 30% increase in work to be performed during the second set of bench press exercise to failure, compared with control conditions, with smaller but sustained improvements through sets 3 and 4. Improvements of this magnitude compare to improved maximal voluntary contraction (MVC) during simultaneously applied artificial electrical stimulation or cerebral magnetic stimulation (34), yet our intervention was solely based on voluntary muscle contraction. Clearly, voluntary controlled intense muscle contractions can still be performed when a previous control system of fatigue is partially removed or blocked. One or a combination of two conclusions can be drawn from this finding: 1) during normal resistance exercise, contractile failure is not governed by exhausted metabolic or contractile properties of the recruited muscle mass; or 2) added motor unit recruitment occurred to supplement metabolically exhausted motor units. Either or both explanations reveal the function of CNS processing of signals altered by palm and central blood volume cooling that result in improved resistance exercise performance.

Considerable scientific debate and commentary exists concerning the likely presence and function of an organized CNS processing of signals influencing muscle fatigue and the perception of fatigue. Such a concept has been called the central governor model (CGM), as has been detailed by Noakes et al. (28) and challenged by others on the basis of the need for more evidence of such a centralized processing center (23) or that such an approach oversimplifies the neural involvement of what is likely to be a more task-dependent trait of exercise-induced fatigue (39). Despite

TABLE 1. The mean difference (%) in RMS, MF, and MDF during eccentric and concentric contractions during the four 85% of 1RM sets of bench press test during TN, PC, and PH conditions (n = 16).

Muscle	EMG Variable (%)	Contraction	Change (%) TN	PH	PC	P
PM	RMS	ECC	47 ± 21	40 ± 20	42 ± 19	0.58
		CON	45 ± 17	38 ± 18	44 ± 19	0.49
	MF	ECC	23 ± 15	21 ± 17	18 ± 19	0.55
		CON	28 ± 13	23 ± 15	26 ± 13	0.43
	MDF	ECC	25 ± 11	20 ± 10	27 ± 12	0.12
		CON	23 ± 9	20 ± 22	26 ± 13	0.58
LTT	RMS	ECC	12 ± 20	19 ± 14	40 ± 18**,††	0.01
		CON	29 ± 29	37 ± 32	53 ± 30**,††	0.01
	MF	ECC	10 ± 11	19 ± 19	18 ± 10	0.20
		CON	18 ± 10	17 ± 12	22 ± 10	0.25
	MDF	ECC	14 ± 11	21 ± 15	20 ± 10	0.31
		CON	22 ± 14	19 ± 12	26 ± 13	0.21
AD	RMS	ECC	23 ± 17	19 ± 16	32 ± 15	0.58
		CON	28 ± 24	17 ± 18	38 ± 44	0.20
	MF	ECC	10 ± 12	12 ± 13	13 ± 13	0.74
		CON	16 ± 9	14 ± 10	21 ± 10	0.06
	MDF	ECC	8 ± 14	10 ± 18	15 ± 16	0.41
		CON	18 ± 12	17 ± 12	24 ± 9	0.10
LT	RMS	ECC	31 ± 26	31 ± 19	36 ± 25	0.65
		CON	24 ± 23	29 ± 26	20 ± 14	0.45
	MF	ECC	14 ± 10	13 ± 8	15 ± 7	0.86
		CON	8 ± 21	12 ± 13	13 ± 9	0.69
	MDF	ECC	16 ± 7	18 ± 8	19 ± 9	0.64
		CON	15 ± 19	18 ± 16	16 ± 12	0.84

Data are presented as mean ± SD.
** $P < 0.01$, PC vs PH conditions.
†† $P < 0.01$, PC vs TN conditions.
CON, concentric; ECC, eccentric; MDF, median frequency; MF, mean frequency; PC, palm cooling; PH, palm heating; RMS, root mean square; TN, Thermoneutral.

these criticisms, our findings can only be explained by the central processing of peripheral input from afferent nerves and/or changes in core blood temperature, and as such, these results fit within the theory of the CGM of the regulation of fatigue and the final cognitive decision to end exercise. We discuss the potential mechanisms that could explain the interactions of PC, neural processing, and resistance exercise performance in the sections that follow.

Potential Mechanisms Explaining the Ergogenic Response to Cooling

Comparison with previous research. Unlike most previous studies using local cooling, we conducted cooling between exercise sets rather than before or after the exercise. More importantly, we did not cool the muscles of interest but the hands and, as such, did not directly alter local muscle physiology. It is difficult to compare our results to previous work because we are the first to show an ergogenic effect of cooling anatomy distal and distant to the muscles used in exercise. It is also important to note that we used a short cooling duration and a limited cooling surface area. The potential mechanisms that explain our findings are logically very different from the work of direct muscle or large body surface cooling (5,6,9,11,16,18,25,33), which we discuss below.

Localized muscle cooling. Our finding that PC increases weight lifted during resistance exercise is similar to a previous study that used ice application (cryotherapy) between weight pulling sets (37). Verducci found that application of ice packs around the shoulder and upper arm for 3 min between sets of arm pulling, to simulate baseball pitching, increased total repetitions and work. Although this methodology differed from ours in the severity of, location, and application of cooling, there was clear similarity in the ergogenic properties of intermittent cold application during recovery intervals. Nevertheless, direct cooling of muscles used in exercise tasks has produced conflicting results. For example, previous studies, which used cooling applied to the skin directly over the exercising muscle, reported decreases in strength or increased fatigue (9,12,16,18,25,32). Conversely, Verducci (37,38) and Burke et al. (4) showed beneficial effects of direct cooling to exercise performance.

Central blood volume cooling. Our findings that PC with negative pressure during rest periods between sets lowered esophageal temperature during exercise are similar to the findings of Grahn et al. (14), where heat extraction from the palm improved aerobic endurance. Certainly, there are differences in exercise mode between the present study and that of Grahn et al. (14). However, these researchers attributed the increase in endurance time to cardiovascular effects caused by the lower core temperature and did not address any possible role of CNS processing. Similar findings were reported by March and Sleivert (24) who cooled the upper body of elite cyclists before a single 70-s bout of intense cycle exercise designed to mimic the 1000-m time trial. Cooling significantly lowered core temperature and RPE during warm-up and improved mean power output during the 70-s test. Interestingly, both studies explained their results on the basis of increased peripheral vasoconstriction of cooled regions, allowing increased blood flow to the working muscles. Our results show that performance benefits also occur from peripheral cooling during intense exercise, but because the region of cooling in this study was small, and the likely redistribution of cardiac output would also be small, an explanation of the improved performance solely based on cardiovascular function is unlikely.

EMG response. Fatigue in a muscle is reflected by specific changes in the EMG recording in the time (RMS) or frequency (MF and MDF) domains (10). An increase in RMS might reflect greater total muscle fiber recruitment for a fixed submaximal external force (10,27). A shift of frequency domain toward lower frequencies would reflect increasing fatigue (3). Despite these claims and interpretations by previous researchers, we also recognize that interpretation of EMG data is complex on the basis of issues of signal amplitude cancellation, M-wave area normalization, and motor unit firing rates that have been well explained by Weir et al. (39). Nevertheless, in our study, the EMG RMS was either the same in most muscle groups, despite a greater number of reps, or increased in the LTT. We also found a shift of MF and MDF toward lower frequencies. Thus, even when recognizing the limitations of muscle EMG signals, our EMG data suggested that cooling resulted in at least the same degree of muscle fatigue at volitional exhaustion but coincident with greater EMG signal and an increased volume of work performed.

Thermal receptor function. Verducci (37,38) and Burke et al. (4) discussed the beneficial effects of cooling on pain reduction as the cause of their positive results. According to the gate control theory described by Melzack and Wall in 1965 (26), physical pain is not a direct result of activation of pain receptor neurons but rather the perception of pain which is modulated by the interaction between different sets of neurons. This theory provides the rationale for interventions to "close the gate" to afferent transmission to the CNS that are eventually processed as perceived pain. Several peripheral stimuli, such as cooling, heating, vibration, and rubbing, can close the gate and diminish pain perception. For example, electrical impulses from transcutaneous electrical nerve stimulation application, or thermal stimulation from heat or cold, can be used to preferentially block or diminish pain (13,19,22).

If the brain integrates thermal signals in addition to other afferent input sources before or during high-intensity resistance training, it is possible that the combined processing of these signals may lead to altered output from the CNS motor center and result in more repetitions during a set of resistance exercise. Our results suggest that acute heat produces a smaller reduction in repetitions in the second set compared with TN. However, during the PC condition, the repetitions in the second set were even more than the repetitions in the first set. Cold receptors are more numerous

(4–10 times) than the warm receptors in hand skin layers (21,31). Cold receptors discharge most vigorously at skin temperatures of 25°C (15,21), whereas warm receptors discharge with increasing skin temperature and reaching a maximum at 45°C–50°C (30). Our subjects' hand temperatures during PC and PH were around 22°C and 40°C, respectively. The greater improvement in both total volume and second set repetitions during PC than during PH may have resulted from a greater number of stimulated cold receptors as well as a stronger stimulus caused by the hand temperature during cooling, being colder than the temperature, producing a maximal response. We speculate that if the mechanism for the ergogenic effect of cooling that we report is caused by interference of pain perception, then the gate control theory would have to extend to after the period of cooling.

Our RPE results, although reported after each set and not during exercise, are interesting in that they reveal an increase in RPE with an increase in core temperature, which is a consistent finding in research of thermoregulation and endurance exercise performance (14). In addition, the RPE was lower during the PC condition than either the PH or TN condition, and differences between trials were largest after the second set, when esophageal temperature was the lowest of any time during exercise. Tucker (35) has proposed that one function of a central governor in explaining exercise performance, fatigue, and volitional exhaustion is to process multiple signals that are expressed collectively in effort perception and, hence, the RPE. Furthermore, such effort perception is then used to anticipate an exercise duration and/or effort at which volitional exhaustion occurs. According to the CGM, then the central processing of signals resulting from the palm and core blood temperature cooling could result in a resetting of the anticipatory response, revealed by the lower RPE associated with the PC trial. Could it be, therefore, that subjects were able to continue to perform more repetitions with cooling simply because they felt better before starting each set?

Our results and the proposed mechanisms for improved resistance exercise performance raise many questions for future research of fatigue and resistance exercise physiology. Future research should separate peripheral cooling from a central blood volume cooling to ascertain whether peripheral cooling versus central blood volume cooling provide independent effects to fatigue and exercise performance. Furthermore, if causing subjects to perceive less effort is a functional component of decreased exercise fatigue, then are there methods to decrease RPE independent of thermoregulatory interventions? If so, do these methods also improve resistance exercise performance?

In conclusion, PC using the RTX between sets of high-intensity bench press exercise resulted in increased repetitions to exhaustion and a greater exercise volume as well as lower HR and RPE during exercise. This improvement in training volume was associated with a greater recruitment of muscle fibers from the LTT and may have involved a delayed central fatigue or a peripheral counterirritation effect caused by output from hand thermal receptors. These results suggest that PC may provide an ergogenic effect to enhance the training response of progressive resistive exercise.

The practical application of our findings might be to improve the quality of resistance training and, subsequently, enhance training adaptations and performance during strength or power activities. Our study, which used 85% of 1RM intensity, four sets, and 3-min between-set intervals, represents a commonly prescribed exercise strength-training session (2). In addition, our findings could have application to the numerous clinical conditions involving chronic muscle fatigue, which are known to benefit from regular exercise. Applying peripheral cooling to muscle, hand, or joint regions in these clinical populations could improve outcomes from exercise therapy, decrease perceptions of fatigue, and cause improvements to quality of life.

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