Comparison of the Effects of Electrical Stimulation and Cold-Water Immersion on Muscle Soreness After Resistance Exercise

Adam R. Jajtner, Jay R. Hoffman, Adam M. Gonzalez, Phillip R. Worts, Maren S. Fragala, and Jeffrey R. Stout

Context: Resistance training is a common form of exercise for competitive and recreational athletes. Enhancing recovery from resistance training may improve the muscle-remodeling processes, stimulating a faster return to peak performance. Objective: To examine the effects of 2 different recovery modalities, neuromuscular electrical stimulation (NMES) and cold-water immersion (CWI), on performance and biochemical and ultrasonographic measures. Participants: Thirty resistance-trained men (23.1 ± 2.9 y, 175.2 ± 7.1 cm, 82.1 ± 8.4 kg) were randomly assigned to NMES, CWI, or control (CON). Design and Setting: All participants completed a high-volume lower-body resistance-training workout on d 1 and returned to the human performance laboratory 24 (24H) and 48 h (48H) postexercise for follow-up testing. Measures: Blood samples were obtained preexercise (PRE) and immediately (IP), 30 min (30P), 24 h (24H), and 48 h (48H) post. Subjects were examined for performance changes in the squat exercise (total repetitions and average power per repetition), biomarkers of inflammation, and changes in cross-sectional area and echo intensity (EI) of the rectus femoris (RF) and vastus lateralis muscles. Results: No differences between groups were observed in the number of repetitions (P = .250; power: P = .663). Inferential-based analysis indicated that increases in C-reactive protein concentrations were likely increased by a greater magnitude after CWI compared with CON, while NMES possibly decreased more than CON from IP to 24H. Increases in interleukin-10 concentrations between IP and 30P were likely greater in CWI than NMES but not different from CON. Inferential-based analysis of RF EI indicated a likely decrease for CWI between IP and 48H. No other differences between groups were noted in any other muscle-architecture measures. Conclusions: Results indicated that CWI induced greater increases in pro- and anti-inflammatory markers, while decreasing RF EI, suggesting that CWI may be effective in enhancing short-term muscle recovery after high-volume bouts of resistance exercise.

Keywords: muscle damage, inflammation, recovery modalities, ultrasonography, C-reactive protein, immune response

Physiological adaptation resulting in improved athletic performance is a function of an athlete exercising at a level that the body is not normally accustomed to. This is typically referred to as the overload principle. These workouts often result in microdamage to the muscle that will stimulate the repair and remodeling processes that ultimately enhance tissue strength and size. The microdamage occurring to skeletal tissue consequent to a resistance-training workout often results in pain and soreness within the muscle. This soreness, commonly known as delayed-onset muscle soreness (DOMS), typically reaches its peak 48 hours after the workout. To enhance recovery from exercise a number of recovery therapies have been proposed. Cryotherapy, compression garments, massage, vibration, and stretching are the most widespread modalities used to improve muscle recovery. Unfortunately, conclusive evidence to support the use of any of these modalities is lacking.

Neuromuscular electrical stimulation (NMES) has long been used in rehabilitation settings for treating multiple sclerosis, stroke, and postoperative patients. NMES treatments have been shown to decrease gait deficits and reduce muscle fatigue in multiple sclerosis patients and increase upper-extremity motor function in stroke patients. In addition, the use of NMES in postoperative patients has been reported to increase isokinetic strength at 6, 12, and 24 weeks after treatment sessions. Several investigators have examined the use of NMES as a potential recovery modality for athletes. While changes in muscle performance and DOMS have been absent after...
NMES, a recent study has shown that throwing velocity can be increased or maintained in college pitchers during competitive performance when treated with NMES between innings. Findings from that study suggest that NMES can improve muscle function and recovery and directly influence athletic performance.

Traditionally, cold-water immersion (CWI) has been used to enhance recovery from exercise. A recent meta-analysis revealed that the use of CWI is effective at reducing DOMS after high-intensity exercise but not after eccentric exercise. In addition, another study evaluated the effects of CWI as a recovery technique after a junior national soccer match, indicating that it may significantly reduce creatine kinase (CK), myoglobin, and C-reactive-protein (CRP) concentrations when compared with a control group (no CWI). The investigators also reported that subjects who were treated with CWI had significantly greater countermovement-jump heights than the control group at 24 and 48 hours after a soccer match. While changes in strength do not appear to be as favorable as changes in power after CWI, existing research appears to support the use of both CWI and NMES as effective modalities for improving recovery. To our knowledge there does not appear to be a study that has compared the effectiveness of CWI and NMES. Therefore, the primary purpose of the current study was to determine the effectiveness of CWI and NMES to enhance recovery after a high-intensity bout of resistance exercise in resistance-trained men. A second objective of the study was to identify changes in markers of muscle damage, inflammation, and immune function consequent to these recovery modalities.

**Methods**

**Study Design**

Participants reported to the human performance laboratory (HPL) on 4 separate occasions. On the first visit (T1), participants were tested for maximal strength (1-repetition maximum [1-RM]) on the barbell back-squat, dead-lift, and barbell split-squat exercises. Before the second visit (T2), participants were instructed to refrain from all forms of exercise for a minimum of 72 hours. In addition, before subsequent exercise sessions, participants were instructed to report to the HPL in a 10-hour fasted state. During T2, participants performed a lower-body resistance-exercise session that consisted of 4 sets of the squat, dead-lift, and barbell split-squat exercises. The rest interval between sets and between all exercises was 90 seconds. The squat exercise was performed with 80% of the participant’s previously measured 1-RM, while the dead-lift and barbell split-squat exercises were performed with 70% of the participant’s previously measured 1-RM. Participants were encouraged to perform as many repetitions as possible but not to exceed 10 repetitions in any set. This protocol was used to simulate a typical lower-body training routine during a hypertrophy phase of training. Participants then reported back to the HPL 24 (T3) and 48 hours (T4) postexercise. During T3 and T4, participants performed 4 sets of the squat exercise using the same loading pattern and rest-interval length as in T2. Participants were asked to complete dietary logs during the 2 days of recovery. Blood samples, ultrasonography, and subjective measures of soreness, pain, and recovery were completed at 5 time points over the course of the study: baseline, immediately postexercise (IP), 30 minutes postexercise (30P), and 24 (before exercise on T3) and 48 hours (before exercise on T4) after T2 (24H and 48H, respectively).

**Participants**

Thirty resistance-trained men with an average age of 6.5 ± 3.5 years of resistance-training experience and an average 1-RM in the squat exercise of 151.0 ± 31.0 kg volunteered to participate in this study. Participants were randomly divided into 1 of 3 treatment groups: control (CON: 23.8 ± 3.0 y, 178.3 ± 5.6 cm, 85.7 ± 5.4 kg), NMES (23.0 ± 3.0 y, 175.9 ± 7.6 cm, 83.5 ± 9.8 kg), or CWI (22.9 ± 2.9 y, 170.6 ± 6.6 cm, 77.1 ± 8.2 kg). After an explanation of all procedures, risks, and benefits, each participant gave his informed consent before participation in this study. The institutional review board of the university approved the research protocol. For inclusion in the study, participants had to have a minimum of 1 year of resistance-training experience, specifically with the squat exercise. They were not permitted to use any additional nutritional supplements or medications while enrolled in the study. Screening for nutritional supplements and performance-enhancing drug use was accomplished via a health history questionnaire completed during participant recruitment. Participants were instructed not to partake in any additional recovery strategies while enrolled in the study, including saunas, stretching routines, foam rollers, massages, and additional hot/cold-water therapy.

**Procedures**

*Neuromuscular Electric Stimulation Therapy.* Participants assigned to NMES were provided with 24 minutes of electrical stimulation immediately after the postexercise blood draw and ultrasound at T2 and postexercise at T3 using a commercially available product (Compex Performance US, DJO, LLC, Vista, CA). All treatments were provided according to the manufacturer’s instructions. Briefly, the participant was placed in a supine position with 3 electrodes placed on each of the quadriceps. Specifically, 1 large electrode with a negative charge was placed at the most proximal point of the upper leg, while 2 small electrodes with positive charges were placed on the belly of the vastus lateralis and vastus medialis. The unit was set to the manufacturer’s recommended recovery mode, while the intensity was set at the highest level considered “tolerable” for the participant. The treatment protocol consisted of 9 sequences, with the first 3 stages lasting for 2 minutes and the remaining 6 for 3 minutes. Frequency of contraction started at 9 Hz, stepping down...
1 Hz per stage to 1 Hz. The participants were asked to remain in a supine position throughout the 24 minutes of treatment.

**Cold-Water Immersion.** The participants in CWI were required to fully immerse their lower body into a metal tub (58.4 × 121.9 cm) filled 22.9 cm high with ice water at 10° to 12°C immediately after the postexercise blood draw and ultrasound on T2 and immediately postexercise on T3. Participants sat in the water up to their umbilicus for 10 minutes. Once the participants completed the 10 minutes in the ice bath they were asked to remain in the HPL for an additional 20 minutes to ensure a similar postexercise intervention opportunity with NMES and CON, who remained in the HPL for 30 minutes in a supine position after their workout.

**Performance Measures.** Before each exercise session, participants performed a standardized warm-up consisting of 5 minutes on a cycle ergometer, 10 body-weight squats, 10 body-weight walking lunges, 10 dynamic walking hamstring stretches, and 10 dynamic walking quadriceps stretches. The 1-RM tests were performed using methods previously described by Hoffman et al.13 Each participant performed 2 warm-up sets using a resistance that was approximately 40% to 60% and 60% to 80% of his perceived maximum. Then, 3 or 4 subsequent trials were performed to determine the 1-RM. A 3- to 5-minute rest period was provided between trials. Trials not meeting the range-of-motion criteria for each exercise were discarded. The squat exercise required the participant to place an Olympic bar across the trapezius muscle at a self-selected location. Each participant descended to the parallel position, which was attained when the greater trochanter of the femur reached the same level as the knee. The participant then ascended until full knee extension. The dead-lift exercise required the participant to grasp an Olympic bar slightly wider than shoulder width with the arms in a fully extended position and feet placed approximately shoulder width. A closed, open, or alternating hand grip was allowed and kept consistent for each participant. From a flexed position, the participant extended his hips and knees until the body assumed an erect standing position. The barbell split-squat 1-RM was assessed only with the dominant leg forward using a prediction formula based on the number of repetitions performed to fatigue using a given weight.14 The barbell split squat required the participant to place an Olympic bar across the trapezius muscle at a self-selected location. The participant assumed an alternating leg stance with the dominant leg forward. For each repetition, the participant flexed the dominant knee until it was over the dominant foot. The trailing knee was lowered to the floor without making contact, while the torso remained erect. The participant pushed off with both legs to return back to the starting position.

Lower-body power during the squat-exercise protocol was measured for each repetition with a Tendo power-output unit (Tendo Sports Machines, Trencin, Slovak Republic). The Tendo unit consists of a transducer attached to the end of the barbell that measured linear displacement and time. Subsequently, bar velocity was calculated and power was determined, based on the weight on the bar (excluding the subject’s body weight). Both peak and mean power output were recorded for each repetition and used for subsequent analysis. These methods have also been previously used,13 and test–retest reliability for the Tendo unit in our laboratory has consistently shown $R > .90$.

**Subjective Measures of Soreness, Pain, and Recovery.** Participants were instructed to assess their subjective feelings of leg soreness and leg pain using a 15-cm visual analog scale (VAS). The scale was anchored by the words *lowest* and *highest* to represent extreme ratings where the greater measured value represented the greater feeling. Questions were structured as “My level of leg soreness is . . .” and “My level of fatigue is . . .” The validity and reliability of the VAS in assessing fatigue and soreness has been previously established.15

Participants were instructed to assess their perceived recovery status at 24H and 48H. The scale was slightly modified from previous research13 and followed a 0- to 10-point rating scale: 0 = very poorly recovered/extremely tired, 2 = not well recovered/somewhat tired, 4 = somewhat recovered, 5 = adequately recovered, 6 = moderately recovered, 8 = well recovered/somewhat energetic, 10 = very well recovered/highly energetic.

**Blood Measurements.** During T2, PRE blood samples were obtained after a 15-minute equilibration period. Additional blood samples were also drawn IP and 30P. All blood samples were obtained using a Teflon cannula placed in a superficial forearm vein using a 3-way stopcock with a male luer-lock adapter. The cannula was maintained patent using an isotonic saline solution (Becton Dickinson, Franklin Lakes, NJ). IP blood samples were taken within 1 minute of exercise cessation. After the resistance-exercise protocol, participants remained in the supine position for the full 30-minute recovery phase before the 30P blood sample was drawn, except for the participants in the CWI groups, who spent the first 10 minutes of the 30 minutes in the ice bath. All T2 blood samples were drawn with a plastic syringe while the participant was in a supine position. During T3 and T4, only PRE blood samples were drawn (24H and 48H, respectively) after a 15-minute equilibration period. These blood samples were obtained from an antecubital arm vein using a 20-gauge disposable needle equipped with a Vacutainer tube holder (Becton Dickinson, Franklin Lakes, NJ). Each participant’s blood samples were obtained at the same time of day during each session.

All blood samples were collected into 2 Vacutainer tubes, one containing K2EDTA. A small aliquot of whole blood was removed from the second tube and used for determination of hematocrit and hemoglobin. The blood in the first tube was allowed to clot at room temperature for 30 minutes and subsequently centrifuged at 3000 g for 15 minutes along with the remaining whole blood from the second
tube. The resulting plasma and serum were placed into separate 1.6-mL micro centrifuge tubes and frozen at -80°C for later analysis.

**Biochemical Analysis.** Myoglobin concentrations were determined using enzyme-linked immunosorbent assays (ELISA) (Calbiotech, Spring Valley, CA, USA). CK was analyzed with the use of a spectrophotometer and a commercially available enzymatic kit (Sekisui Diagnostics, Charlottetown, PE, Canada) per manufacturer’s instructions. Serum immunoreactivity values were determined using a BioTek Eon spectrophotometer (BioTek, Winooski, VT, USA). To eliminate interassay variance, all samples for a particular assay were thawed once and analyzed in the same assay run by a single technician. All samples were run in duplicate with a mean coefficient of variation of 5.73% for myoglobin and 2.99% for CK.

Circulating levels of interleukin-6 (IL-6), IL-10, and CRP were assessed by Magpix (EMD Millipore, Billerica, MA, USA). IL-6 and IL-10 were assayed by the human cytokine/chemokine panel 1 (EMD Millipore, Billerica, MA, USA), while CRP was assayed by the human cardiovascular-disease panel 3 (EMD Millipore, Billerica, MA, USA) according to manufacturer guidelines. Samples were analyzed in duplicate, with average coefficients of variation of 11.47% for IL-6, 10.94% for IL-10, and 7.22% for CRP.

Hemoglobin was analyzed in triplicate from whole blood using an automatic analyzer (Hemocue, Cypress, CA, USA). Hematocrit was analyzed in triplicate from whole blood via microcentrifugation (Statspin Critspin, Westwood, MA, USA) and microcapillary technique. Coefficients of variation for each assay were 3.68% for hemoglobin and 0.73% for hematocrit. Plasma-volume shifts after the workout were calculated using the formula established by Dill and Costill.16

**Ultrasonography.** Measurements of cross-sectional area (CSA), and echo intensity (EI) were collected via noninvasive ultrasonography at the same time that blood samples were obtained. EI is an arbitrary measure of muscle quality, based on a grayscale analysis of the muscle.17 All measurements were collected on the vastus lateralis (VL) and rectus femoris (RF) of the participants’ dominant leg and performed by the same technician to minimize error in the same fashion as previously stated; however, the sampling location was determined by 50% of the straight-line distance between the greater trochanter and the lateral epicondyle of the femur. Sites of ultrasonography were marked and maintained consistent through the duration of the study.

Once images were collected, analysis was completed using Image J software (National Institutes of Health, USA, version 1.45s). CSA and EI (ICC3,1 = .976, SEM = 1.604) were measured on the transverse image sweep using a known distance of 1 cm within the image to calibrate to software. Briefly, CSA was measured by tracing the outline of the RF or VL in Image J using the freehand tool, while EI was determined using the standard histogram function, a quantification of grayscale with arbitrary units ranging from 0 to 256 in the area previously determined for CSA. When traced in Image J, this area excluded the muscle fascia, to minimize the effects on grayscale.

**Dietary Logs.** Participants were instructed to record as accurately as possible everything they consumed during workout days T2 and T3. Participants were instructed not to eat or drink (except water) within 10 hours of reporting to the HPL for subsequent visits. FoodWorks dietary-analysis software (McGraw Hill, New York, NY) was used to analyze the dietary recalls for total kilocalorie intake and macronutrient distributions (carbohydrate, protein, and fat).

**Statistical Analysis**

All performance and biochemical changes were analyzed using a repeated-measures analysis of variance (ANOVA). In the event of significant F ratio, pairwise comparisons using the Bonferroni adjustment were employed for significant main effects, while a 1-way ANOVA was employed for significant interactions. Before analysis all data were assessed to ensure normal distribution and homogeneity of variance and sphericity. Changes in dietary composition were also analyzed using a 1-way ANOVA. Results were considered significant at an alpha level of P < .05. All data are reported as mean ± SD.

In addition, data were analyzed using magnitude-based inferences, calculated from 90% confidence intervals, as previously described by Batterham and Hopkins.19 Based on the relatively small sample size and a movement toward this analysis in the sport-science literature, we decided to administer this analytical procedure if parametric analysis revealed a P value of .051 to .225. Differences between IP and all subsequent time
points were calculated for each treatment group (control, NMES, and CWI). The IP time point at T2 was selected as a covariate because no treatment intervention occurred before that point, and it was subsequent to the primary resistance bout. These change scores were then analyzed via a published spreadsheet, with the smallest nontrivial change set at 20% of the grand standard deviation. All data are expressed as a mean effect ± SD, with percent chances of a positive or negative outcome. Qualitative inferences based on quantitative chances were assessed as <1% almost certainly not, 1% to 5% very unlikely, 5% to 25% unlikely, 25% to 75% possibly, 75% to 95% likely, 95% to 99% very likely, and >99% almost certainly.

**Results**

No significant differences were observed between groups in training experience, 1-RM squat strength, and anthropometric measures. In addition, no significant differences were noted in daily dietary consumption between the groups. The average daily caloric intake during the recovery days was 5271 ± 1422 kcal, composed of 200 ± 77 g fat, 601 ± 181 g carbohydrates, and 277 ± 115 g of protein. The relative protein intake for all subjects was a total of 3.39 ± 1.37 g/kg body mass over the course of the 2 recovery days.

**Performance Variables**

Performance variables are depicted in Table 1. A significant main effect for time \((P < .001)\) was seen with a significantly \((P < .001)\) greater number of repetitions in the squat exercise completed on T2 than on both T3 and T4. No significant interaction \((P = .250)\) or main effect for group \((P = .245)\) was observed for total squat repetitions. In addition, no significant interaction \((P = .663)\) or main effect for group \((P = .490)\) was observed for average power per repetition. A significant main effect for time \((P < .001)\) was observed, with significantly \((P < .01)\) greater power per repetition observed at T2 than at T3 and T4.

**Subjective Measures of Soreness, Pain, and Recovery**

Significant elevations from PRE were observed in all groups for the VAS in regard to both soreness and pain \((P < .001)\). However, no differences were noted between the groups for either soreness \((P = .733)\) or pain \((P = .358)\). When collapsed across groups, subjective measures of soreness increased \((P < .001)\) from PRE \((0.6 ± 1.0)\) cm to IP \((9.3 ± 4.1)\) cm and then decreased at 30P \((5.1 ± 3.5)\) cm. Soreness was elevated \((P < .001)\) at 24H \((7.9 ± 4.2)\) cm and continued to rise \((P < .001)\) at 48H \((10.0 ± 4.3)\) cm. With groups combined, subjective measures of pain increased \((P < .001)\) from PRE \((0.4 ± 0.7)\) cm to IP \((9.0 ± 4.3)\) cm and decreased \((P < .001)\) at 30P \((3.7 ± 2.9)\) cm. Feelings of pain were significantly higher than PRE \((P < .001)\) at 24H \((5.7 ± 3.9)\) cm and remained elevated \((P < .001)\) at 48H \((8.0 ± 4.6)\). Similarly, no interactions for soreness \((P = .932)\) or pain \((P = .586)\) were observed. A time effect \((P = .028)\) for perceived recovery was observed, indicating that individuals felt more recovered at 24H \((4.90 ± 2.20)\) than at 48H \((4.17 ± 2.02)\). No significant differences were noted in perceived recovery between groups at any time point.

**Biochemical Analysis**

Changes in CK concentrations are depicted in Figure 1. Significant elevations were seen from PRE to IP \((P < .001)\), 24H \((P < .001)\), and 48H \((P < .001)\). However, no between-groups differences \((P = .479)\) or interactions \((P = .405)\) were observed. Changes in myoglobin concentrations are shown in Figure 2. No significant interaction \((P = .168)\) or main effect for group \((P = .252)\) was reported. Significant elevations from PRE to IP were seen in all groups \((P = .001)\) and continued to elevate \((P < .001)\) from IP to 30P. Inferential-based analysis indicated that the increases in myoglobin from IP to 30P were likely \((81.6\%)\) and very likely \((98.4\%)\) greater in NMES and CWI when compared with CON, respectively.

Changes in IL-10 concentrations are depicted in Figure 3. No significant interaction of IL-10 \((P = .127)\)

<table>
<thead>
<tr>
<th>Table 1  Performance Characteristics for Neuromuscular Electrical Stimulation (NMES), Cold-Water Immersion (CWI), and Control (CON)</th>
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<tr>
<td><strong>Total repetitions</strong></td>
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<td>NMES 23.1 ± 7.2</td>
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<tr>
<td>CWI 25.3 ± 7.9</td>
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<td>CON 27.9 ± 7.9</td>
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<tr>
<td><strong>Average power (W/repetition)</strong></td>
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<td>NMES 475.7 ± 130.4</td>
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<td>CWI 426.1 ± 81.2</td>
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<td>CON 423.2 ± 114.9</td>
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or main effect for group \((P = .947)\) was observed. However, a significant main effect for time \((P < .001)\) was seen; IL-10 concentrations were higher at 30P \((47.49 \pm 42.91 \text{ pg/mL})\) than at PRE \((22.54 \pm 23.96 \text{ pg/mL}; P = .002)\), IP \((24.91 \pm 22.78 \text{ pg/mL}; P = .013)\), 24H \((24.36 \pm 27.68 \text{ pg/mL}; P = .002)\), and 48H \((26.54 \pm 34.42 \text{ pg/mL}; P = .040)\). Inferential-based analysis indicated that IL-10 concentrations were likely (83.6%) elevated to a greater magnitude in CWI from IP to 30P than with NMES. However, the decrease from IP to 48H was likely greater in magnitude in CWI than CON (89.8%).

No significant interaction \((P = .487)\) or main effects for time \((P = .267)\) or group \((P = .341)\) were observed for IL-6.

Changes in CRP can be observed in Figure 4. No significant interactions \((P = .216)\) or main effects for group \((P = .182)\) were observed. However, a significant main effect for time \((P = .010)\) was noted. Pairwise comparisons indicated that CRP concentration at 24H was significantly higher than at 30P \((P = .024)\) and 48H \((P < .001)\). When changes in CRP concentration were assessed via magnitude-based inferences, the increase

Figure 1 — Changes in creatine kinase (CK) concentration on the first day of training from preexercise (PRE) to immediately postexercise (IP) and 30 minutes postexercise (30P) on the first day of training and to preexercise on the second (24H) and third (48H) days of training in neuromuscular electrical stimulation (NMES), cold-water immersion (CWI), and control (CON) groups. *Significant elevation from PRE for all groups combined \((P < .001)\).

Figure 2 — Changes in myoglobin concentration on the first day of training from preexercise (PRE) to immediately postexercise (IP) and 30 minutes postexercise (30P) on the first day of training and to preexercise on the second (24H) and third (48H) days of training in neuromuscular electrical stimulation (NMES), cold-water immersion (CWI), and control (CON) groups. *Significant increase from PRE for all groups combined \((P < .001)\). #Likely difference in change from IP in NMES compared with CON. ^Very likely difference in change from IP in CWI compared with CON.

Figure 3 — Changes in interleukin-10 (IL-10) concentration from preexercise (PRE), immediately postexercise (IP), and 30 minutes postexercise (30P) on the first day of training to preexercise on the second (24H) and third (48H) days of training in neuromuscular electrical stimulation (NMES), cold-water immersion (CWI), and control (CON) groups. *Likely difference in change from IP compared with NMES. #Likely difference in change from IP compared with CWI.

Figure 4 — Changes in C-reactive protein (CRP) concentration from preexercise (PRE), immediately postexercise (IP), and 30 minutes postexercise (30P) on the first day of training to preexercise on the second (24H) and third (48H) days of training in neuromuscular electrical stimulation (NMES), cold-water immersion (CWI), and control (CON) groups. *Possible difference in change from IP compared with NMES. #Likely difference in change from IP compared with CWI.
from IP to 24H in CWI was likely (91.5%) greater than with NMES. However, change in NMES was possibly (69.8%) less than that seen in CON.

No significant differences were noted for the change in plasma volume between groups at IP (–14.47% ± 4.06%). However, plasma-volume shifts were significantly different for CWI (–3.36% ± 3.38%) than with NMES (1.10% ± 3.17%; P = .049) or CON (1.45% ± 5.15%; P = .031) at 30P. Blood variables were not corrected for plasma-volume shifts due to the importance of molar exposure at the tissue level.

Muscle-Architecture Changes

Changes in RF EI are presented in Figure 5. When EI results were collapsed across time, no significant differences were noted between groups (P = .893), but when collapsed across groups for time (P < .001), EI for the RF was significantly greater at IP than at any other time point. A trend toward a significant interaction (P = .064) was noted. When analyzed using magnitude-based inferences, decreases in RF EI from IP to 48H were likely greater in CWI than in CON (91.8%) and NMES (83.9%). When collapsed across groups, a significant (P < .001) increase in RF CSA was seen at IP (15.88 ± 2.81 cm²) compared with PRE (15.01 ± 2.78 cm²), 30P (15.39 ± 2.51 cm²), 24H (14.98 ± 2.51 cm²), and 48H (15.08 ± 2.57 cm²). However, no significant interaction (P = .336) or main effect for group (P = .776) was observed.

EI of the VL for all groups combined was significantly decreased (P = .012) from IP (63.27 ± 6.67) to 30P (61.40 ± 6.75). In addition, VL EI at both IP and 30P was significantly elevated (P < .001) compared with PRE (57.49 ± 7.57), 24H (57.05 ± 7.26), and 48H (55.57 ± 8.86). No significant interaction (P = .241) or main effect for group (P = .865) was observed. VL CSA was significantly (P < .01) elevated from PRE (33.56 ± 5.39 cm²) to IP (36.94 ± 5.73 cm²) and decreased at 30P (34.98 ± 5.49 cm²). CSA remained elevated at 24H (34.42 ± 5.88 cm²) and 48H (35.11 ± 5.66 cm²); the difference between 24H and 48H was statistically significant (P = .003). No significant interaction (P = .562) or main effect for group (P = .468) was observed.

Discussion

The high-volume, moderate-intensity training program performed at T2 resulted in muscle damage, as reflected by significant elevations in both myoglobin and CK concentrations. The significant elevations in EI at IP and 30P and significant performance decrements during the subsequent exercise sessions at T3 and T4 provided further support for the damaging effects of the T2 workout. This is consistent with previous research using a similar exercise protocol.13 Neither CWI nor NMES appeared to be any more effective than CON in enhancing performance recovery during the 48-hour postexercise period from T2. However, differences in the response of muscle-damage and inflammatory markers (eg, greater increases in myoglobin, CRP, and IL-10 concentrations postexercise) in CWI compared with NMES and CON suggest that ice-water baths may delay recovery within the first 30 minutes after exercise but may improve the inflammatory profile on subsequent days, without resulting in actual performance differences after an acute muscle-damaging workout.

Performance decrements observed in this study were similar to those previously reported by Hoffman et al.13 However, the number of repetitions performed at
T2 appeared to be greater in the previous study. This is likely due to differences in the participants recruited. While Hoffman et al examined experienced resistance-trained competitive athletes, our study used experienced resistance-trained recreational athletes, resulting in lower power and repetitions completed on the initial testing day (T2). Considering that recreational athletes may not be adapted or willing to push past a point of discomfort to perform all desired repetitions, the results of this study should be placed in the appropriate context: recovery of performance in recreationally trained individuals with resistance-training experience.

Neither modality employed in this study appeared to provide any benefit regarding performance recovery. This contrasts with Leeder et al, who suggested that CWI can enhance power performance, but is consistent with other studies that were unable to demonstrate the efficacy of NMES after a muscle-damaging protocol. It is important to note that the meta-analysis published by Leeder et al included only studies that monitored power via explosive movements such as vertical jump and did not include studies using a resistance-exercise protocol similar to the one employed in this study.

The attenuation of subjective feelings of DOMS has been the focus of many studies. While several investigations have documented an attenuation of DOMS after CWI and NMES, others have suggested that reductions of soreness may depend on the type of exercise performed. Endurance-type activity has been suggested to respond more favorably to these recovery modalities than exercise modes that require heavy eccentric actions, such as resistance exercise.

While the use of NMES and CWI appears equivocal based on performance measures, differences in biomarkers of muscle damage and inflammation suggest that CWI may reduce the acute recovery process compared with NMES or CON. Myoglobin is thought to be a more sensitive indicator of acute skeletal-muscle damage than CK. This is likely related to the relatively smaller molecular size of myoglobin compared with CK (17,800 vs 40,000 Daltons, respectively). The smaller myoglobin molecule appears to leak out of the damaged tissue at a faster rate than the larger CK molecule. Considering that the resistance-training performance at T2 was similar for all groups, the myoglobin response for CWI suggests that a cold-water bath immediately postworkout may exacerbate the acute damage response to the exercise stress. These data, however, contrast with the finding of others who reported the CWI may actually attenuate the acute myoglobin response. These differences may be related to the training protocol used (resistance exercise for this study compared with a soccer match or repeat shuttle runs) and possible differences in plasma-volume shifts. The CK response at 24H and 48H does suggest a similar magnitude of muscle damage at those time points between the groups. It is possible that immersion in cold-water or ice-water baths briefly limits the onset of the muscle-recovery and -remodeling process. However, its physiological significance is not clear.

CRP is thought to have both proinflammatory and anti-inflammatory properties. The increase in circulating CRP concentrations at 24H is consistent with other investigations examining muscle damage after team-sport activity and a plyometric-exercise bout. The importance of CRP may be related to its role in activating the classical complement cascade and phagocytosis, which is important for subsequent muscle repair. Likewise, CRP also induces the release of anti-inflammatory cytokines such as IL-1 receptor agonist and IL-10. Considering that no change was seen in IL-6 and there was no difference in performance recovery, it is likely that the elevation in CRP was related to its role in muscle recovery. In addition, elevations in CRP at 24H are greater in our study than in other studies. They are, however, below the previously established upper limit for healthy individuals of 10 μg/mL and, therefore, within the expected range. Although speculative, the elevations seen in CRP concentrations after CWI may have stimulated a greater immune response and potentially accelerated muscle remodeling. To our knowledge this appears to be the first study to have examined the influence of NMES as a recovery modality and its effect on changes in CRP concentrations after resistance exercise. Although the change in CRP from IP during NMES was likely lower than CON at 24H, its effect on muscle remodeling after an acute bout of high-volume resistance exercise is not clear. It is possible the CRP response after the use of NMES may have a greater anti-inflammatory effect postexercise, possibly delaying muscle recovery. This may be reflected in the EI responses seen between the groups.

IL-10 concentration underwent a marked increase at 30P after CWI. IL-10 is thought to have anti-inflammatory properties, due to its ability to block the production of proinflammatory cytokines. Its elevation likely serves as a balance to the proinflammatory response observed in CRP at 24H. Previous studies have suggested that changes in IL-10 concentrations after cold therapy may depend on level of exposure. Topical cooling was reported to not induce a significant increase in IL-10, while whole-body cryotherapy significantly elevated IL-10 concentrations. During this study, subjects in CWI were submerged up to their umbilicus in cold water, exposing a large surface area to cold. This may have contributed to the magnitude in the IL-10 response compared with NMES and CON conditions.

EI has been suggested as a useful tool to assess muscle damage and has been validated as a measure of muscle quality. A higher EI is indicative of a decrease in muscle quality compared with a lower EI. Elevations in EI for both RF and VL seen in this study reflect the decrease in muscle quality or extent of muscle damage that occurred after the exhausting workout at T2. These results are also consistent with another study that demonstrated significant elevations in EI after an exhausting bout (4 × 10 RM at 80% 1-RM) of resistance exercise focused on recruiting the elbow flexors. An interesting finding was that participants in CWI were more likely to experience a decrease in RF EI at 48H than were
CON and NMES. Although others have suggested that this may be related to a decrease in edema after CWI, the lack of any change in RF CSA does not provide any support for this hypothesis. However, considering that CRP has been reported to have both proinflammatory and anti-inflammatory properties, it is possible that the higher CRP response seen at 24H for CWI may have provided a greater stimulation for muscle recovery than in the other groups.

**Conclusions**

In conclusion, the results of this study suggest that an acute session of moderate-intensity, high-volume lower-body resistance training induces significant elevations in muscle-damage markers and subsequent performance decrements. However, neither CWI nor NMES appears to provide any greater benefit than CON regarding performance recovery, but changes in CRP and IL-10 after CWI during recovery suggest that CWI may enhance both the proinflammatory and anti-inflammatory responses responsible for muscle remodeling. This latter benefit may be reflected by the lower EI seen at 48H in CWI. Future research is warranted examining the efficacy of these specific recovery therapies after prolonged high-intensity training.

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**References**


