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Prolonging the duration of cooling does not enhance recovery following a marathon

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Runners commonly utilize cryotherapy as part of their recovery strategy. Cryotherapy has been ineffective in mitigating signs and symptoms of muscle damage following marathon running and is limited by its duration of application. Phase change material (PCM) packs can prolong the duration of cooling. This study aimed to test the efficacy of prolonging the duration of cooling using PCM on perceptual recovery, neuromuscular function, and blood markers following a marathon run. Thirty participants completed a marathon run and were randomized to receive three hours of 15°C PCM treatment covering the quadriceps or recover without an intervention (control). Quadriceps soreness, strength, countermovement jump (CMJ) height, creatine kinase (CK), and high sensitivity C-reactive protein (hsCRP) were recorded at baseline, 24, 48, and 72 hours after the marathon. Following the marathon, strength decreased in both groups ($P < .0001$), with no difference between groups. Compared to baseline, strength was reduced 24 ($P = .004$) and 48 hours after the marathon ($P = .008$) in the control group, but only 24 hours ($P = .028$) in the PCM group. Soreness increased ($P < .0001$) and CMJ height decreased ($P < .0001$) in both groups, with no difference between groups. Compared to baseline, CMJ height was not reduced on any days in the PCM group but was reduced in the control group 24 ($P < .0001$) and 48 hours ($P = .003$) after the marathon. CK and hsCRP increased in both groups ($P < .0001$). Although the marathon run induced significant muscle damage, prolonging the duration of cooling using PCM did not accelerate the resolution of any dependent variables.

KEYWORDS

cryotherapy, endurance, exercise recovery, muscle damage

1 | INTRODUCTION

Long-distance endurance running, such as a marathon, can result in a range of signs and symptoms associated with exercise-induced muscle damage (EIMD). A reduction in functional performance, strength loss, soreness, inflammation, and oxidative stress have all been reported following marathon running.[1–6] Similarly, the deleterious effects of EIMD following a bout of unaccustomed eccentrically biased exercise are well documented.[7] However, the etiology,

temporal sequence of events, extent of muscle fiber damage, and magnitude of the inflammatory response are different following marathon running versus eccentric exercise.[8,9] For example, following eccentric exercise, full recovery normally occurs within two to seven days.[10] In contrast, even the most elite, experienced, and well-trained runners are not spared from the symptoms of EIMD.[5] Following a marathon run, muscle, cardiac, and inflammatory markers have been reported to remain elevated at day eight[1] and the repair of focal muscle fiber damage has been reported to take up to eight weeks.[11] Ultimately, timely recovery from the symptoms associated with EIMD is critical.

Marathon runners have opted for a range of recovery strategies to mitigate their symptoms after training and competitive runs in an attempt to accelerate the regenerative process. Some popular strategies include cryotherapy,[12] compression,[13] and nutritional interventions.[14,15] However, few of these studies have successfully implemented a recovery intervention to ameliorate strength loss[15] or soreness[13] following marathon running. Nevertheless, one of the most popular cryotherapy modalities among athletes is cold water immersion (CWI). Previously, Ihsan et al[16] and Leeder et al[17] both concluded that CWI is more effective in alleviating symptoms of EIMD following exercise with a high metabolic cost, such as endurance, high intensity, or team sport exercise, than following isolated eccentric exercise. Furthermore, in their review, White and Wells proposed that CWI was especially beneficial for recovery from metabolically stressful exercise because of its ability to restore cardiovascular function. Thus, the efficacy of CWI for attenuating the effects associated with EIMD may be dependent on the exercise mode.

Endurance type protocols characteristically result in a greater level of systemic hyperthermia and an elevated thermal load compared with isolated resistance exercise. For this reason, it is unlikely that CWI would sufficiently reduce body temperature for long enough to diminish the extensive secondary phase of muscle damage that occurs following a marathon. Indeed, it seems counterintuitive to expect a recovery intervention, administered for on average 12.6 minutes at a mean temperature of 13°C,[18] to have any considerable influence on the mechanisms that occur following a marathon run lasting anywhere over two hours. Prolonging the duration of tissue cooling has previously been suggested as a critical component in reducing the secondary muscle damage response[19,20] and mitigating the overall extent of tissue damage.[21–24]

A longer duration of cooling can be achieved by utilizing phase change material (PCM) packs that freeze at 15°C. The influence of three hours of PCM cooling on muscle temperature, core temperature, and the cardiovascular response has recently been established and compared with a temperature matched CWI protocol.[25] In the aforementioned study, both PCM and CWI reduced superficial and deep muscle temperature, core temperature, and modulated sympathetic tone to the same magnitude in rested individuals. However, this effect only lasted for the 15-minute duration of CWI while it was maintained throughout the entire 3-hour duration of PCM cooling. The influence of prolonged PCM cooling on acute physiological recovery has also been established following isolated eccentric quadriceps exercise[26,27] and following soccer match play.[28,29] Given that EIMD is a multifaceted process, an intervention strategy capable of treating the symptoms of EIMD after they manifest following eccentric exercise may not be as effective following endurance exercise. Therefore, it remains unknown whether prolonging the duration of cryotherapy will accelerate recovery following a marathon run. Thus, this study aimed to investigate the effects of prolonged PCM cooling on the recovery of strength, soreness, functional performance, and blood markers of muscle damage (creatine kinase; CK) an index of inflammation (high sensitivity C-reactive protein; hsCRP) following the completion of a marathon run. It was hypothesized that, due to the prolonged dose of cooling, PCM would successfully accelerate recovery of the signs and symptoms associated with EIMD resulting from a marathon run.

2 | METHODS

2.1 | Participants

A power calculation was conducted based on the available literature on marathon running to determine an adequate sample size for this study. Estimates were made of the expected change and the inter-subject variation in change for each marker of muscle damage.[2,6,15] Assuming that the control group would have the expected responses, estimates were made on how much lower that response would need to be in the PCM treatment group. Thus, it was estimated that there would be 80% power to detect a 10% difference in strength loss between treatments (SD: 8.0%, based on % change from baseline data for muscle damage) at an alpha level of 0.05 using a one-sided t test with a total of 15 participants per group. As a result, thirty healthy volunteers, 11 males and 19 females, participated in the study (mean ± SD; age, 34 ± 8 years; height, 169.4 ± 10.7 cm; body mass, 68.1 ± 12.9 kg). Participants were runners with varying degrees of marathon experience (number of previous marathons: 5 ± 6) whose expected completion times were 4:10 ± 0:42 hours. Female participants verbally confirmed that they were premenopausal. All participants were non-smokers with no history of recent illness or other diseases and were free from lower extremity injury within the past 6 months. In the five days prior to the run, and for the

duration of the study, participants were instructed to refrain from taking NSAIDS, nutritional supplements, pharmacological interventions, therapeutic interventions, and strenuous exercise unrelated to the present study. Prior to participation, volunteers were informed of the procedures and provided written, informed consent. The institutional research ethics committee, in line with the Declaration of Helsinki, approved all procedures.

2.2 | Experimental design

Participants reported to the research laboratory for a total of four days. On the first day of data collection (baseline testing) participants were equally and randomly assigned in a pseudorandomized fashion to either a control (n = 15) or PCM treatment (n = 15) group based upon their predicted finish time. Participants were paired and equally assigned to either group based upon both predicted finish time and sex in a pseudorandomized fashion, in an attempt to account for possible sex differences in response to marathon running. Participants were then familiarized with all of the testing procedures prior to baseline data collection of all dependent variables. Measurements of all outcome variables were also recorded 24, 48, and 72 hours after the marathon following completion of the marathon run. All data were collected in the same order, by the same investigator, using the same data collection instruments, and occurred at the same time of day at all time points, regardless of the location of the marathon run. Participants were recruited across a large pool of competitive marathons consisting of road routes with similar terrains. The courses were 38%-43% downhill and 37%-41% uphill, with a total elevation of 894.5 ± 281.4 feet. The following marathons were completed by study participants: New York City (n = 26), Philadelphia (n = 1), Brooklyn (n = 1), London (n = 1), and Cape Cod (n = 1). The environmental conditions on the day of each race were similar (11.6 ± 2.3°C), and no marathon was completed while it was precipitating or under "hot and/or humid" weather. Participants ran at a self-selected pace and were allowed to consume fluids, electrolytes and/or food ad libitum during the marathon but were asked to avoid consuming any supplements containing BCAAs, protein, antioxidants, or caffeine. Participants in the control group were specifically advised to refrain from utilizing any recovery modality for the duration of the study. Additionally, participants in both groups were instructed to refrain from showering until at least 4 hours following completion of the race. This was to ensure that participants assigned to the treatment group did not enhance their muscular rewarming by showering immediately following 3 hours of PCM application. Thus, a 1-hour buffer period was be added for a total of 4 hours.

2.3 | Blood sampling and analysis

Capillary blood was drawn by way of a finger prick. Blood samples were always performed prior to any activity being initiated by the participants. The fingertip was cleaned with 95% ethanol before an automatic lancet device was used to puncture the skin to draw capillary blood. The first drop of blood was removed to prevent possible contamination. A 30 μL sample of capillary blood was obtained using a 30-μL pipette (Microsafe Tubule, Safe-Tec Clinical Products, Pennsylvania, USA) for the enzymatic measurement of CK concentration. The sample was then immediately analyzed (Reflotron® Plus System, Roche Diagnostics, Basel, Switzerland) using a CK test strip (Reflotron CK, Roche Diagnostics, Mannheim, Germany). A 10 μL sample was obtained in a 10 μL pipette for the immune-chromatographic assay of hsCRP (Nano-Checker 710, Nano-Ditech Corporation, Cranbury, NJ, USA) using a hsCRP test strip (Nano-Check hsCRP, Nano-Ditech Corporation, Cranbury, NJ, USA) and following the manufacturer's guidelines. A reliability trial conducted before data collection revealed that the inter-day coefficient of variation (CV) for analysis of CK was 7.9%. The intra-sample CV is 15% for hsCRP (Nano-Ditech Corporation, Cranbury, NJ, USA), and a reliability trial conducted before data collection revealed that the inter-day CV for analysis of hsCRP was 17.7%.

2.4 | Soreness assessment

Soreness in the lower limbs was assessed by having participants perform a two-legged full body squat to 90° knee flexion and verbally report the discomfort level for each leg using a 0 to 10-point visual analogue scale (VAS; 0 = no discomfort, 10 = too painful to squat to 90°).

2.5 | Countermovement jump

Countermovement jumps were performed using the Optojump optoelectric system (Bolzano, Italy). A reliability trial conducted before data collection revealed that the inter-day CV for this protocol was 3.6%. Prior to data collection, participants were given an unlimited number of practice jumps to be performed at ~50% maximal effort, until their jumping technique was performed correctly according to the following instructions. Participants started the movement upright with their feet shoulder width apart and their hands fixed to their hips and, when prompted by a verbal cue, rapidly descended into a self-selected squat position and jumped vertically with maximum force. Participants were instructed to maintain no bend in their knees at the peak of the jump. If a participant bent their knees at the peak of the jump, the jump did not count toward a maximal effort. Participants were

also instructed to land in the same position as take off and keep their hands on their hips for the full movement to minimize any influence of arm swing on performance. Once the participant's technique was correct, participants performed three maximal efforts, separated by approximately 60 seconds of standing recovery; the mean of the three jumps was used for analysis. CMJs were performed prior to strength testing.

2.6 | Strength assessment

Maximum isometric voluntary contraction (MIVC) of the knee extensors was measured on a dynamometer (Biodex System 3, Shirley, NY, USA). Participants were seated with the trunk at 90° of flexion, and the knee at 80° flexion. The lateral femoral condyle was aligned to the center of rotation of the dynamometer. Participants performed one practice submaximal isometric contraction followed by two MIVCs, held for 5 seconds each with 15 seconds rest between each contraction. Participants were given strong, standardized verbal encouragement for the duration of each contraction. The average of the two peak torques was recorded. Knee extensor MIVC testing was performed on the right and left leg in a randomized sequence. Peak torque values for both legs were averaged. Strength over 72 hours after the marathon is expressed as a percentage of baseline strength.

2.7 | Phase change material cooling intervention

During baseline testing, participants were fitted with appropriately sized generic athletic shorts (Eastbay brand), into which four PCM packs (Glacier Tek USDA BioPreferred PureTemp PCM, Plymouth, MN, USA) "frozen" at 15°C were applied directly onto the skin over the quadriceps of both legs, two packs per leg. Based on our previous studies (three-[25] and six-hour duration of PCM application[26,27]), it was established that the participants would wear the PCM over the quadriceps of both legs for a total of three hours to have a balance between efficacy and practicality of the treatment. Participants receiving three-hour PCM treatment began the intervention within 1:20 ± 0:34 hours of finishing the marathon. Participants were allowed to continue with activities of daily living while wearing the PCM. After three hours of treatment, the PCM was removed. Participants in the control group did not receive any form of intervention.

2.8 | Statistical analysis

The effect of PCM cooling or control on strength loss, soreness, CMJ height, CK, and hsCRP over the 72 hours following the marathon was assessed using 2 × 4 treatment by time mixed-model ANOVA. The two levels for the treatment factor were PCM cooling and control. The four levels for the time factor were baseline, 24, 48, and 72 hours after the marathon after the marathon. Absolute change of strength and CMJ height were reported as percent change from baseline in order to account for inter-individual variability. Absolute baseline values were compared between treatment groups using independent t test.

Cohen's d effect sizes (ES) were calculated to estimate the magnitude of the treatment effects, with the magnitude of effects considered either small (0.20-0.49), medium (0.50-0.79), and large (>0.80).[30] Normality of distribution for all data sets was examined using the Shapiro-Wilk test and where necessary data were logged transformed to establish a normal distribution (CK and hsCRP were log-transformed). Mauchly's test of sphericity was used to assess assumptions of sphericity and, where necessary, Greenhouse-Geisser corrections were applied. Where significant differences between treatments at any particular time interval were present, post-hoc comparisons were used to identify differences between treatments in response to the marathon. Baseline values were examined for differences between treatment groups using independent *t* tests. Additionally, Pearson product-moment correlation coefficients were used to assess the relationship between soreness and number of previous marathons. Statistical analyses were performed using SPSS v.21 (IBM, Armonk, NY, USA). Mean ± SD are reported in the subsequent sections and throughout the tables and figures. A *P*-value of less than 0.05 was considered statistically significant.

3 | RESULTS

A summary of participant characteristics and marathon completion times is presented in Table 1.

3.1 | Blood markers

At baseline, CK values were not different between groups ($P = .224$; PCM treatment: 119.0 ± 71.0 $U{\cdot}L^{-1}$, control: 169.2 ± 139.0 $U{\cdot}L^{-1}$). At baseline, hsCRP values were not different between groups ($P = .267$; PCM treatment: 1.03 ± 0.82 μg/mL, control: 0.77 ± 0.34 μg/mL). Following the marathon, CK and hsCRP increased over time in both groups, with no difference between groups (Table 2).

3.2 | Soreness

At baseline, soreness values were not different between groups ($P = .254$; PCM treatment: 0.2 ± 0.8, control: 0.0 ± 0.0,

TABLE 1 Participant characteristics and marathon completion times

Treatment	n	Age (years)	Height (cm)	Weight (kg)	# Previous marathons	Expected finish time	Actual finish time
PCM	**15**	**36 ± 8**	**170.9 ± 10.0**	**67.1 ± 11.5**	**3 ± 6**	**4:21 ± 0:42**	**4:23 ± 0:53**
Female	9	35 ± 9	164.6 ± 6.7	60.5 ± 6.7	4 ± 6	4:16 ± 0:43	4:29 ± 0:51
Male	6	37 ± 8	180.3 ± 5.8	77.1 ± 10.1	10 ± 7	3:34 ± 0:22	3:40 ± 0:20
Control	**15**	**33 ± 9**	**167.9 ± 11.5**	**69.1 ± 14.4**	**6 ± 7**	**3:59 ± 0:40**	**4:11 ± 0:48**
Female	10	31 ± 8	162.3 ± 7.4	62.8 ± 12.3	3 ± 7	4:26 ± 0:46	4:29 ± 0:58
Male	5	36.6 ± 9	179.0 ± 10.4	81.7 ± 9.5	2 ± 2	4:11 ± 0:36	4:13 ± 0:47
Total	**30**	**34 ± 8**	**169.4 ± 10.7**	**68.1 ± 12.9**	**5 ± 6**	**4:10 ± 0:42**	**4:17 ± 0:50**
Between group comparisons		$P = .338$	$P = .454$	$P = .689$	$P = .143$	$P = .169$	$P = .543$

Note: Values are mean ± SD. Finish times are reported as hour: minutes (h:mm).

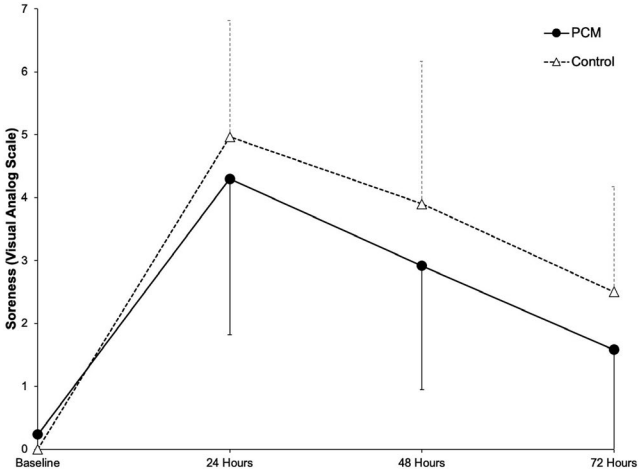

FIGURE 1 Subjective reports of quadriceps soreness on a 0-10 scale (0 = no discomfort, 10 = too painful to squat to 90°) for the PCM treatment and control groups before and over 72 hours (24, 48, and 72 hours) following the marathon. Following the marathon, soreness was increased in both groups over the 72 hours ($P < .0001$)

VAS 0-10). Following the marathon, perceptions of soreness increased in both groups over time (Figure 1; $F = 76.4$, $P < .0001$, ES = 3.31), with no treatment ($P = .264$) or interaction effect observed ($P = .195$). Peak soreness was inversely correlated with number of prior marathons ($P = .005$, $r = -0.497$), but this effect was not different across treatments ($P = .544$).

3.3 | Countermovement jump height

There were technical issues with measuring CMJ for seven participants throughout the duration of the study. Thus, only 12 and 11 participants in the control and PCM treatment groups, respectively, were included in the treatment by time analysis of the CMJ data. Jump height was not different between groups at baseline ($P = .764$; PCM treatment: 21.2 ± 4.4 cm, control: 21.9 ± 5.5 cm). Jump height decreased following the marathon (Figure 2; $F = 15.9$, $P < .0001$, ES = 1.74), with no treatment ($P = .273$) or interaction effect observed ($P = .198$). Compared with baseline values, the control group experienced compromised jump height 24 hours (84.5 ± 7.5% of baseline; $P < .0003$, ES = 4.34) and 48 hours following the marathon (88.4 ± 9.0%; $P = .003$, ES = 2.69), while the PCM treatment group did not exhibit compromised jump height at any point over the 72 hours following the marathon (24 hours: 86.8 ± 16.7% of baseline, $P = .150$, 48 hours: 97.5 ± 17.1%, $P = .999$, 72 hours: 98.6 ± 11.8%, $P = .999$).

3.4 | Strength

Average knee extension peak torque was not different between groups at baseline ($P = .771$; PCM treatment: 157.9 ± 36.6 Nm, control: 154.0 ± 35.3 Nm). Over the 72 hours following the marathon, strength decreased in both groups (Figure 3; $F = 15.0$, $P < .0001$, ES = 1.46), with no group ($P = .535$) or interaction effect observed ($P = .828$). Relative to baseline strength, the control group experienced strength loss at 24 hours (86.8 ± 11.4% of baseline; $P = .004$, ES = 2.40) and 48 hours (92.2 ± 8.2%; $P = .008$, ES = 1.98) post-marathon, while the PCM treatment group experienced strength loss only at 24 hours (88.0 ± 14.9%; $P = .028$, ES = 1.67), but not 48, or 72 hours post-marathon.

4 | DISCUSSION

This study investigated whether administering three hours of PCM cooling following a marathon run would accelerate recovery. The marathon led to decreases in muscle function, increases in perceptions of soreness, and increases in blood markers of muscle damage (CK) and inflammation (hsCRP). Contrary to the hypothesis, and unlike our previous work,[26–29] there was no difference in the rate of recovery between

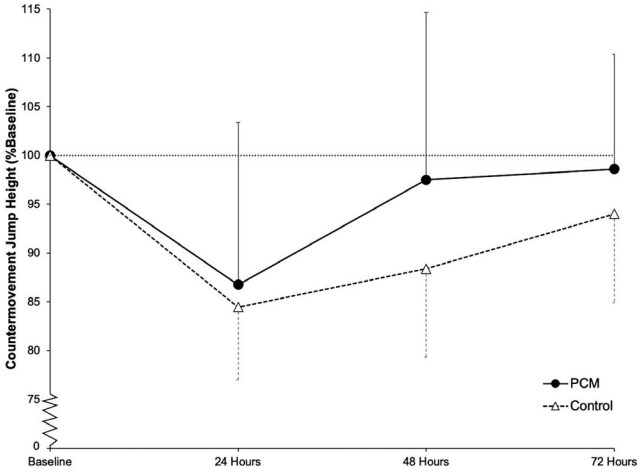

FIGURE 2 Percentage change from baseline in countermovement jump (CMJ) height for the PCM treatment and control groups before and over 72 hours (24, 48, and 72 hours) following the marathon. Following the marathon, CMJ height was impaired in both groups ($P < .0001$) but, compared to baseline, was not different at any time for PCM treatment while jump height was impaired below baseline at 24 ($*P = .0003$) and 48 hours ($*P = .003$) for the control group

the PCM treatment and control groups. These results indicate that prolonged PCM cooling was not an effective recovery strategy when administered after running a marathon.

The findings of the present study are in agreement with the only other study to have previously investigated the effectiveness of cryotherapy on recovery from a marathon.[12] Wilson et al demonstrated that compared with control, neither CWI nor whole body cryotherapy was effective in accelerating recovery of strength loss, soreness, muscle function, and blood markers of muscle damage and inflammation after a marathon run. However, since muscle soreness was largely absent by 48 hours following the marathon in their study, coupled with no effect from the marathon on strength loss, their findings indicated that the marathon run was not strenuous enough to elicit a damage response, thus making it difficult to determine the effectiveness of their intervention. Furthermore, the authors reported that their participants were trained endurance runners and the course of their marathon consisted of an outdoor route comprised of predominantly grass and unpaved footpaths, with some short concrete sections which were run at a self-selected pace. Comparably, the participants in the present study were less trained, had longer marathon completion times (4:17 vs 3:48 hours), experienced a 12% and 13% reduction in MIVC 24 hours following the marathon in the PCM and control groups, respectively, had elevated soreness 48 hours after the marathon that had not recovered in either group by 72 hours following the marathon, and increased blood markers of muscle damage and inflammation. Hence, the damage response in the present study was greater than that reported by Wilson et al. The 13% strength loss and 5 out of 10 pain reported by the control group 24 hours after the marathon in the present study is comparable to values reported by Howatson et al; 18% strength loss and 4 out of 10 pain 24 hours after their marathon). Thus, in the present study, there was sufficient damage from the marathon to detect a benefit from the PCM cooling intervention.

Although compared to control, there was no benefit from PCM treatment for accelerating recovery of strength following the marathon, MIVC returned to baseline in the PCM treatment group by 48 hours but not until 72 hours after the marathon in the control group. The change in a muscles force-generating capacity provides a good indication of the status of the whole muscle and can be used to indirectly quantify EIMD.[31] In the present study, MIVC was measured in an isolated muscle group, and therefore, it is likely that MIVC did not reflect the complete picture of EIMD associated with activities involving multiple muscle groups such as marathon running.[32] Hence, CMJ performance, which reflects impairments in the stretch-shortening cycle function,[33] may be used concurrently with MIVC to provide a better picture of dynamic muscle function. Although in the present study there was also no significant benefit from PCM for accelerating CMJ height, it is notable that the PCM treatment group did not exhibit compromised jump height at any point over the 72 hours following the marathon. In comparison, CMJ height was impaired for 48 hours after the marathon in the control group. Significant decrements in CMJ height have previously been reported for 48 hours following marathon running.[5] One previous study has examined the effects of CWI on CMJ height following a half-marathon,[34] reporting minimal impairment of CMJ height and subsequently no effect of CWI in accelerating recovery of CMJ height after the half-marathon (4% reduction). In comparison, another study measured CMJ height following a full marathon and showed a 10% and 5% reduction in jump height at 24 and 48 hours, respectively, with no benefit from a nutritional intervention in accelerating recovery of CMJ height.[14] Thus, although PCM did not significantly enhance recovery of functional performance, the participants in the control group exhibited greater impairments in CMJ height than the participants in Clifford's (2016) study, while both CMJ and MIVC had recovered by 48 hours in the PCM treatment group. Therefore, although not significant, PCM clearly had some effect in attenuating the decrements in performance.

The present study expands upon the findings of previous studies implementing prolonged durations of PCM cooling following high intensity isolated eccentric contraction of a single muscle group[26,27] or following a soccer match.[28,29] Based on these data, it is possible that the cooling effect from the PCM packs applied locally to the quadriceps was not large enough to act systemically on a damage response occurring across several muscle groups. This is especially possible when considering that the marathon likely resulted

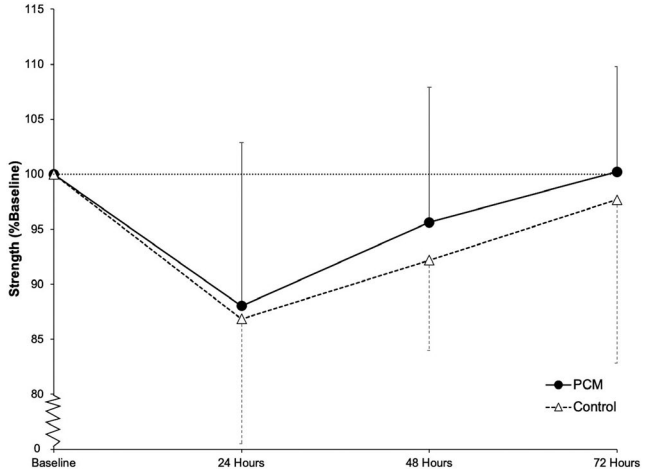

FIGURE 3 Isometric strength loss of the quadriceps (presented as a percentage of baseline strength loss) for the PCM treatment and control groups before and over 72 hours (24, 48, and 72 hours) following the marathon. Strength was reduced over the 72 hours after the marathon ($P < .0001$), with no difference between groups. Following the marathon, strength loss was reduced below baseline at 24 hours ($*P = .004$) and 48 hours ($*P = .008$) in the control group and only at 24 hours in the PCM treatment group ($*P = .028$)

in a thermal load much greater than any of the exercises in our previous work. However, due to the nature of a competitive marathon environment, participant temperature or thermal perception were not measured in this study. Therefore, although highly plausible, any inference about an elevated thermal load is simply hypothetical. Nevertheless, it is likely that the magnitude of cooling occurring from the application of PCM only to the quadriceps was likely insufficient. Attention should be paid to the magnitude of thermal load exerted by the exercise when considering cryotherapy treatment. Previous studies that have successfully implemented CWI for the accelerated recovery of strength have all done so following exercise in the heat, which results in increased thermal strain and central fatigue.[16,35–36] In the aforementioned studies, recovery of strength was concomitant with the amelioration of voluntary activation and core temperature. Therefore, under a large thermal load, CWI may alleviate some of the exercise-induced cerebral perturbations either directly or via its effect on core temperature.[16] In the case of long-distance endurance running, when the thermal load is significantly elevated and multiple muscle groups are damaged, it might be most beneficial to combine the effects of multiple cryotherapy modalities. In practice, an athlete might opt to begin their recovery regimen with CWI, quickly decreasing their intramuscular and core temperature, and once completed they could apply PCM over muscle groups they wish to keep cool in order to maintain the reduction of both peripheral and central temperatures. Although speculative, this multifaceted cryotherapy approach could allow the athlete to sustain the treatment effect from CWI for a longer duration in the immediate post-exercise period all the while allowing the athlete to return to normal post-exercise activities (eg meal, relaxation, recreational activities). Future research should examine the impact of PCM application on body temperatures following exercise of metabolic nature resulting in an elevated thermal load such as marathon running to determine whether a greater cooling dose is required to elicit the previously demonstrated beneficial effects following eccentric[26,27] and team sport exercise.[28,29]

It is important to acknowledge the limitations of this study. Firstly, the CV values for the hsCRP measure were high and the noise in the measure may have masked possible differences between conditions. Secondly, prior to the marathon run, we failed to collect data on the training volume or training history of our participants other than number of

TABLE 2 Response of indices of muscle damage (serum Creatine Kinase; CK) and inflammation (high sensitivity C-reactive protein; hsCRP) in the blood before (baseline) and over 72 hours (24, 48, and 72 hours) after the marathon run in the PCM and control groups

	CK ($U \cdot L^{-1}$)		hcCRP (μg/mL)	
Time	**PCM**	**Control**	**PCM**	**Control**
Baseline	119 ± 70 (2.00 ± 0.28)	169 ± 138 (2.11 ± 0.31)	1.03 ± 0.82 (−0.07 ± 0.26)	0.77 ± 0.34 (−0.15 ± 0.17)
24 hours	893 ± 471 (2.87 ± 0.30)	841 ± 372 (2.87 ± 0.24)	7.72 ± 5.28 (0.79 ± 0.31)	7.38 ± 4.56 (0.80 ± 0.27)
48 hours	419 ± 289 (2.51 ± 0.35)	547 ± 363 (2.64 ± 0.31)	3.63 ± 1.89 (0.51 ± 0.22)	4.27 ± 2.29 (0.56 ± 0.28)
72 hours	328 ± 193 (2.42 ± 0.32)	378 ± 416 (2.36 ± 0.47)	2.26 ± 1.12 (0.30 ± 0.24)	4.23 ± 5.80 (0.43 ± 0.39)
Time effect	$P < .0001$	$P < .0001$	$P < .0001$	$P < .0001$
Treatment effect	$P = .623$		$P = .655$	
Treatment by time effect	$P = .309$		$P = .412$	

Note: Values are mean ± SD and are presented as absolute value (log-transformed value).

previous marathons. Since there was an inverse correlation between soreness response and experience, additional information about runner experience would have added value to this correlation. Additionally, there was a difference between the number of previous marathons in the male control and PCM groups. The inverse correlation between soreness response and experience could explain, in part, why the strength recovery data may have favored the PCM group. However, experience had no significant effect in either the female or male participants for both groups or for the PCM group. Thirdly, due to the nature of marathon environments with large numbers of runners, retrieving one's belongings following the race is delayed. Thus, the PCM was not applied until on average 80 minutes following completion of the marathon. During such a long-distance run, muscle damage is likely induced before the marathon run is concluded; thus, an overlap exists between the individual exercising and muscle damage occurring. This overlap was likely to be substantially smaller in previous studies showing a beneficial effect from PCM where the exercise took between 40 minutes[26,27] and 90 minutes[28,29] to complete and where PCM were applied within 10,[26,27] 30,[29] and 45 minutes[28] of exercise cessation. Animal models have previously shown that a window of opportunity for intervention with cryotherapy lies within the first 30 minutes after injury.[37] Thus, in the present study, a combination of exercise that had high metabolic stress for a prolonged duration (on average exceeding four hours) and a delay in the application of PCM cooling might have limited the potential of the intervention to accelerate recovery. In an ideal scenario, PCM cooling would be administered as soon as possible upon cessation of exercise. Although participants in the control group did not receive a recovery garment fitted with PCM, the compression pressure exerted by the PCM was not a confounding factor as in a pilot study with 14 subjects wearing the shorts fitted with the PCM packs (unpublished data from our lab), the average compression pressure as measured by a Kikuhime pressure monitor (Kikuhime; TT, 160 Medi Trade, Søleddet, Denmark) was 5.0 mm Hg, which is negligible compared with the pressure needed to influence recovery through compression garments.[38]

5 | PERSPECTIVE

One of the most popular cryotherapy modalities utilized by endurance runners in an attempt to accelerate recovery of EIMD is CWI in the form of an ice bath. To date, the only study investigating the effects of cryotherapy on recovery following a marathon was unable to show any recovery benefit.[12] Our study was the first to examine the application of cryotherapy following marathon running which induced significant strength loss and soreness. Although the results of the present study were null, there was some visual evidence to suggest that prolonged PCM cooling accelerated recovery of soreness, strength, and CMJ height compared to control. From an athletic recovery perspective, these findings do not completely rule out the use of prolonged PCM cooling for recovery following a marathon. Athletes might be interested in implementing PCM cooling for subjective recovery in the place of, or concomitant to, ice baths following endurance running.

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REFERENCES

1. Bernat-Adell MD, Collado-Boira EJ, Moles-Julio P, et al. Recovery of inflammation, cardiac, and muscle damage biomarkers after running a marathon. *J Strength Cond Res*. 2019;29. https://doi.org/10.1519/JSC.0000000000003167
2. Kratz A, Lewandrowski KB, Siegel AJ, et al. Effect of marathon running on hematologic and biochemical laboratory parameters, including cardiac markers. *Am J Clin Pathol*. 2002;118(6):856-863.
3. Millet GY, Martin V, Lattier G, Ballay Y. Mechanisms contributing to knee extensor strength loss after prolonged running exercise. *J Appl Physiol*. 2003;94(1):193-198.
4. Nicol C, Komi PV, Marconnet P. Fatigue effects of marathon running on neuromuscular performance. *Scand J Med Sci Sports*. 1991;1(1):18-24.
5. Petersen K, Hansen CB, Aagaard P, Madsen K. Muscle mechanical characteristics in fatigue and recovery from a marathon race in highly trained runners. *Eur J Appl Physiol*. 2007;101(3):385-396.
6. Suzuki K, Nakaji S, Yamada M, et al. Impact of a competitive marathon race on systemic cytokine and neutrophil responses. *Med Sci Sports Exerc*. 2003;35(2):348-355.
7. Clarkson PM, Newham DJ. Associations between muscle soreness, damage, and fatigue. *Adv Exp Med Biol*. 1995;384:457-469.
8. Tee JC, Bosch AN, Lambert MI. Metabolic consequences of exercise-induced muscle damage. *Sports Med*. 2007;37(10):827-836.
9. White GE, Wells GD. Cold-water immersion and other forms of cryotherapy: physiological changes potentially affecting recovery from high-intensity exercise. *Extrem Physiol Med*. 2013;2(1):26.
10. Paulsen G, Mikkelsen UR, Raastad T, Peake JM. Leucocytes, cytokines and satellite cells: what role do they play in muscle damage and regeneration following eccentric exercise? *Exerc Immunol Rev*. 2012;18:42-97.
11. Warhol MJ, Siegel AJ, Evans WJ, Silverman LM. Skeletal muscle injury and repair in marathon runners after competition. *Am J Pathol*. 1985;118(2):331-339.

12. Wilson LJ, Cockburn E, Paice K, et al. Recovery following a marathon: a comparison of cold water immersion, whole body cryotherapy and a placebo control. *Eur J Appl Physiol*. 2018;118(1):153-163.
13. Hill JA, Howatson G, van Someren KA, Walshe I, Pedlar CR. Influence of compression garments on recovery after marathon running. *J Strength Cond Res*. 2014;28(8):2228-2235. https://doi.org/10.1519/JSC.0000000000000469
14. Clifford T, Allerton DM, Brown MA, et al. Minimal muscle damage after a marathon and no influence of beetroot juice on inflammation and recovery. *Appl Physiol Nutr Metab*. 2016;42(3):263-270.
15. Howatson G, McHugh MP, Hill JA, et al. Influence of tart cherry juice on indices of recovery following marathon running. *Scand J Med Sci Sports*. 2010;20(6):843-852.
16. Ihsan M, Watson G, Abbiss CR. What are the physiological mechanisms for post-exercise cold water immersion in the recovery from prolonged endurance and intermittent exercise? *Sports Med*. 2016;46(8):1095-1109.
17. Leeder J, Gissane C, van Someren K, Gregson W, Howatson G. Cold water immersion and recovery from strenuous exercise: a meta-analysis. *Br J Sports Med*. 2012;46(4):233–240.
18. Bleakley C, McDonough S, Gardner E, Hopkins JT, Glasgow P, Davison GW. Cold-water immersion (cryotherapy) for preventing and treating muscle soreness after exercise. *Cochrane Database Syst Rev*. 2012;15(2):CD008262.
19. Merrick MA, Rankin JM, Andres FA, Hinman CL. A preliminary examination of cryotherapy and secondary injury in skeletal muscle. *Med Sci Sports Exerc*. 1999;31(11):1516.
20. Swenson C, Swärd L, Karlsson J. Cryotherapy in sports medicine. *Scand J Med Sci Sports*. 1996;6(4):193-200.
21. Bleakley CM, Glasgow P, Webb MJ. Cooling an acute muscle injury: can basic scientific theory translate into the clinical setting? *Br J Sports Med*. 2012;46(4):296-298.
22. Enwemeka CS, Allen C, Avila P, Bina J, Konrade J, Munns S. Soft tissue thermodynamics before, during, and after cold pack therapy. *Med Sci Sports Exerc*. 2002;34(1):45-50.
23. Ihsan M, Watson G, Lipski M, Abbiss CR. Influence of postexercise cooling on muscle oxygenation and blood volume changes. *Med Sci Sports Exerc*. 2013;45(5):876-882.
24. Knight KL. . *Cryotherapy in sport injury management*. Champaign, IL: Human Kinetics; 1995.
25. Kwiecien SY, McHugh MP, Goodall S, Hicks KM, Hunter AM, Howatson G. Exploring the efficacy of a safe cryotherapy alternative: physiological temperature changes from cold water immersion vs prolonged phase change material cooling. *Int J Sports Physiol Perform*. 2019;2:1288-1296.
26. Kwiecien SY, McHugh MP, Howatson G. The efficacy of cooling with phase change material for the treatment of exercise-induced muscle damage: pilot study. *J Sports Sci*. 2018;36(4):407-413.
27. Kwiecien SY, O'Hara DJ, McHugh MP, Howatson G. Prolonged cooling with phase change material enhances recovery and does not affect the subsequent repeated bout effect following exercise. *Eur J Appl Physiol*. 2020;120(2):413-423.
28. Brownstein CG, Ansdell P, Škarabot J, et al. The effect of phase change material on recovery of neuromuscular function following competitive soccer match-play. *Front Physiol*. 2019;10:647.
29. Clifford T, Abbott W, Kwiecien SY, Howatson G, McHugh MP. Cryotherapy reinvented: application of phase change material for recovery in elite soccer. *Int J Sports Physiol Perform*. 2018;13(5):584-589.
30. Durlak JA. How to select, calculate, and interpret effect sizes. *J Pediatr Psychol*. 2009;34(9):917-928.
31. Warren GL, Lowe DA, Armstrong RB. Measurement tools used in the study of eccentric contraction induced injury. *Sports Med*. 1999;27(1):43-59.
32. Byrne C, Twist C, Eston R. Neuromuscular function after exercise-induced muscle damage: theoretical and applied implications. *Sports Med*. 2004;34(1):49-69.
33. Komi PV. Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *J Biomech*. 2000;33(10):1197-1206.
34. Wiewelhove T, Schneider C, Döweling A, et al. Effects of different recovery strategies following a half-marathon on fatigue markers in recreational runners. *PLoS One*. 2018;13(11):e0207313.
35. Minett GM, Duffield R, Billaut F, Cannon J, Portus MR, Marino FE. Cold-water immersion decreases cerebral oxygenation but improves recovery after intermittent-sprint exercise in the heat. *Scand J Med Sci Sports*. 2014;24(4):656-666.
36. Pointon M, Duffield R, Cannon J, Marino FE. Cold water immersion recovery following intermittent-sprint exercise in the heat. *Eur J Appl Physiol*. 2011;112(7):2483-2494.
37. Merrick MA, McBrier NM. Progression of secondary injury after musculoskeletal trauma—A window of opportunity? *J Sport Rehabil*. 2010;19(4):380-388.
38. Hill JA, Howatson G, van Someren K, et al. The effects of compression garment pressure on recovery from strenuous exercise. *Int J Sports Physiol Perform*. 2017;12(8):1078-1084.

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