International Journal of Sports Physiology and Performance, 2017, 12, 402-409
http://dx.doi.org/10.1123/ijspp.2016-0186

Human Kinetics
ORIGINAL INVESTIGATION

Recovery From Exercise-Induced Muscle Damage: Cold-Water Immersion Versus Whole-Body Cryotherapy

Abd-Elbasset Abaïdia, Julien Lamblin, Barthélémy Delecroix, Cédric Leduc, Alan McCall, Mathieu Nédélec, Brian Dawson, Georges Baquet, and Grégory Dupont

Purpose: To compare the effects of cold-water immersion (CWI) and whole-body cryotherapy (WBC) on recovery kinetics after exercise-induced muscle damage. ***Methods:*** Ten physically active men performed single-leg hamstring eccentric exercise comprising 5 sets of 15 repetitions. Immediately postexercise, subjects were exposed in a randomized crossover design to CWI (10 min at 10°C) or WBC (3 min at –110°C) recovery. Creatine kinase concentrations, knee-flexor eccentric (60°/s) and posterior lower-limb isometric (60°) strength, single-leg and 2-leg countermovement jumps, muscle soreness, and perception of recovery were measured. The tests were performed before and immediately, 24, 48, and 72 h after exercise. ***Results:*** Results showed a very likely moderate effect in favor of CWI for single-leg (effect size [ES] = 0.63; 90% confidence interval [CI] = –0.13 to 1.38) and 2-leg countermovement jump (ES = 0.68; 90% CI = –0.08 to 1.43) 72 h after exercise. Soreness was moderately lower 48 h after exercise after CWI (ES = –0.68; 90% CI = –1.44 to 0.07). Perception of recovery was moderately enhanced 24 h after exercise for CWI (ES = –0.62; 90% CI = –1.38 to 0.13). Trivial and small effects of condition were found for the other outcomes. ***Conclusions:*** CWI was more effective than WBC in accelerating recovery kinetics for countermovement-jump performance at 72 h postexercise. CWI also demonstrated lower soreness and higher perceived recovery levels across 24–48 h postexercise.

Keywords: eccentric, cold air, fatigue

Cooling the body to accelerate the recovery of performance is now widely used by coaches and athletes.[1] One of the theoretical bases of cooling the body to accelerate recovery is a decrease in inflammation due to exposure to the cold environment.[2,3] Inflammation occurs immediately after exercise-induced muscle damage and is prolonged over time.[4] Although this inflammatory response is required to heal muscle damage,[4] an attenuation of this inflammation may have beneficial effects on recovery of muscle performance.[2]

The principle of cold-water immersion (CWI) is to immerse a part or all of the body (except the head) in a cold-water bath in which the temperature is below 15°C for a duration of 10 to 12 minutes.[5] In contrast, whole-body cryotherapy (WBC) consists of body exposure to very cold air at a temperature between –110°C to –195°C in a specifically designed room for a total duration of 3 to 4 minutes.[3]

Studies have shown the ability of CWI to improve strength and power recovery kinetics after exercise-induced muscle damage in comparison with a passive recovery.[6]

Similarly, Hausswirth et al[7] and Ferreira-Junior et al[8] found a beneficial effect of WBC on recovery kinetics in comparison with far-infrared and passive recovery conditions, respectively. Two systems are frequently used for WBC: cold air[7] or liquid nitrogen.[8] In the cold-air system, the chamber is closed and subjects have to traverse a first room at a temperature of –10°C. They traverse a second room at a temperature of –60°C and stay 3 minutes in a room at a temperature of –110°C. In the liquid nitrogen system, subjects are exposed 3 minutes at a temperature of –110°C. In this system the head is not exposed to cold.

CWI and WBC have a significant effect on reducing some biological markers of muscle damage[3,9] and inflammation.[3] Additionally, these recovery strategies have also been shown to provide a beneficial effect on subjectively perceived soreness the day after exercise.[6,9] However, the efficacy of CWI is not clearly established despite the large volume of research performed in this area.[9] Roberts et al[10] found that regular postexercise CWI may attenuate muscular adaptations to resistance training.

In a meta-analysis, Poppendieck et al[11] compared the effects on recovery of CWI vs WBC. They found a slightly higher average effect size on performance recovery for CWI. However, in this review only 2 studies regarding WBC effects on recovery kinetics were reported. Differences between CWI or WBC protocols make the comparison between both recovery strategies difficult. Parameters such as magnitude of strength loss after the exercise implemented or the type of exercise task used vary from one study to another.[8,12]

To our knowledge, no study has compared CWI with WBC for effects on muscle performance recovery kinetics, biochemical markers of muscle damage, and perceived soreness. Therefore, the aim of this study was to compare the effects of CWI and WBC on recovery kinetics after exercise-induced muscle damage.

Methods

Experimental Design

In a randomized crossover design, subjects performed 5 sets of 15 eccentric knee flexor contractions on 1 leg to induce muscle

Abaïdia, Delecroix, Baquet, and Dupont are with the Multidisciplinary Research Unit Sport, Health and Society, Université de Lille, Lille, France. Lamblin is with the Research Dept, LOXC Lille Métropole, Camphin-en-Pévèle, France. Leduc is with the University of Picardie Jules Verne, Amiens, France. McCall is with Edinburgh Napier University, Edinburgh, Scotland. Nédélec is with the French National Inst of Sport, Expertise and Performance (INSEP), Paris, France. Dawson is with the University of Western Australia, Crawley, Australia. Address author correspondence to Grégory Dupont at gregory.dupont@univ-lille2.fr.

damage. Immediately after, subjects performed either a CWI or a WBC recovery session. Each session was separated by 2 weeks. Subjects performed a battery of tests before the exercise (baseline values), immediately after (0 h), and 24 , 48, and 72 hours after the exercise-induced muscle damage.

Subjects

Of the 14 initial participants, 4 subjects were excluded: 2 incurred an injury, and 2 did not respect the inclusive criteria. Ten physically active men (mean ± SD age 23.4 ± 4 y, height 178 ± 9 cm, body mass 73.4 ± 12.0 kg) participated in this study: They had not incurred any hamstring injury during the prior 6 months. Subjects were asked not to undertake any physical activity at least 48 hours before the completion of the first test (baseline). They were instructed not to perform any physical activity; not to consume protein, alcohol, or caffeine; nor to perform any recovery strategies in the 24 hours before the exercise-inducing muscle damage and also during the 3 days after the exercise. The level of hamstring soreness and the level of fatigue had to be lower than 5 (moderately sore/tired) on a 0 to 10 point scale (0 = not sore; 10 = very, very sore) and (0 = not tired; 10 = very, very tired), respectively. Each subject answered a questionnaire before each session to check if these criteria were respected. If the participants did not respect these inclusion criteria they were excluded from the study. All subjects provided written informed consent to participate to this study. This study was made in accordance with the local ethical committee on biomedical research (No. 5915052012) and the standards set by the Declaration of Helsinki.

Methodology

Subject Allocation. Subjects were allocated in a randomized and balanced order to both conditions: CWI and WBC. Dominant and nondominant legs were assigned to a condition in a randomized and balanced order. The order of recovery session was also randomized, and 4 combinations were used: nondominant leg + CWI, dominant leg + CWI, nondominant leg + WBC, dominant leg + WBC. Randomization of participants was conducted by using a random-numbers generator (www.randomization.com) to assign subjects to their groups. To avoid cross-adaptation consequences of the contralateral leg on force values and recovery kinetics,[13] half of the group started with CWI and the other half with WBC.

Familiarization and Tests. Subjects performed 2 sessions of familiarization consisting of 5 repetitions of the test at a low intensity and 2 repetitions at a maximal intensity. Two sessions were performed to determine the level of reliability for eccentric force, isometric force, and single-leg countermovement jump (CMJ-1L) tests. Reliability statistics were calculated between trial 1 and trial 2 (Table 1) at the baseline time point. Trial 1 and trial 2 were separated by 72 hours. Baseline values were recorded before the experimental protocol. During each session, the investigator verbally encouraged subjects to perform at their best. Encouragements were standardized. Each session was preceded by a standardized warm-up.

Warm-Up. The warm-up comprised 2 sets of 10 repetitions of concentric contractions with 1-minute recovery between sets on an isokinetic dynamometer (Con-Trex MJ, CMV AG, Dübendorf, Switzerland). The subjects performed knee flexions at 60°/s at a fixed intensity of 60 N/m.

Exercise-Induced Muscle Damage. Subjects performed a hamstring exercise (knee flexion) task using the tested leg on an isokinetic dynamometer (as described). The exercise task comprised 5 sets of 15 eccentric contractions at a speed of 60°/s, interspersed by a 3-minute recovery. Each contraction lasted 3 seconds, and recovery time between contractions lasted 3 seconds.

Subjects were seated on the dynamometer chair with the hip joint at 75°. Full extension of the leg was considered as 0° for dynamic tests (range of motion 0–90°). The distal shin pad of the dynamometer was attached 3 to 4 cm proximal to the lateral malleolus by using a strap. During muscle contractions, to minimize extraneous body movements, straps were applied across the chest, pelvis, and midthigh. The alignment between the dynamometer rotational axis and the knee joint rotation axis (lateral femoral condyle) was checked at the beginning of each trial. Gravity's effect on torque was recorded on each subject throughout the range of motion, and this was used to correct torque measurements during all tests. The isokinetic dynamometer was calibrated according to the recommendations of the manufacturer. Thirty minutes after completing exercise the subjects noted the global intensity using the modified rate of perception scale from 0 (rest) to 10 (maximal).[14]

Recovery Sessions. These took place 5 minutes after the last test was performed, which corresponds to 0 hours after the exercise task. During CWI, in a standing position, subjects wore swimming trunks and were immersed up to the neck in a cold-water pool at 10°C for 10 minutes.[5] During WBC, subjects were in a cryocabin (Cryo Sana, Mecacel, France) producing cold air from liquid nitrogen at a temperature of –110°C for 3 minutes.[8] Skin was directly exposed to cold, except the head (which was outside the top of the cabin), and the hands and feet were protected by gloves, socks, and clogs while inside the cabin. Exercise and recovery sessions were performed in a room with a temperature of 21°C.

Force Tests. Subjects were tested on an isokinetic dynamometer (as previous) in knee flexion at different speeds and on different types of muscular contractions: eccentric force (60°/s) and isometric force (5 s at 60°). Subjects performed 2 trials interspersed by 3-minute recovery for each kind of contraction. Force was

Table 1 Reliability of Outcomes Measured During the Experimental Protocol

	Trial 1	Trial 2	ES (90% CI)	TE (90% CI)	ICC (90% CI)	CV
Eccentric force 60°/s (N/m)	194.7 ± 29.1	200.5 ± 44.3	0.15 (–0.6 to 0.9)	16.76 (12–28.7)	.85 (.6–1)	12%
Isometric force 60° (N)	144.2 ± 26	144.8 ± 28	0.02 (–0.8 to 0.8)	4.05 (2.7–7.8)	.98 (.9–1)	3.9%
CMJ-1L (cm)	17.5 ± 4.2	16.8 ± 4.6	–0.16 (–1.04 to 0.7)	0.85 (0.5–2.5)	.97 (.8–.99)	9.4%

Note: Trial 1 and trial 2 are, respectively, the first and second trial performed by the subjects after the familiarization for each outcome concerned.

Abbreviations: CI, confidence interval; CMJ-1L, single-leg countermovement jump; CV, coefficient of variation; ES, effect size; ICC, intraclass correlation coefficient; TE, typical error.

tested immediately postexercise (0 h), then at 24, 48, and 72 hours postexercise.

CMJ-1L and 2-Leg Countermovement Jump. Subjects performed the jumps on a force plate (Kistler Instruments, Hampshire, UK). They kept the foot of the tested leg in contact with the platform with their hands on the hips. Their knee was flexed to a self-selected depth in response to the instruction to jump as high as possible and to land on the same leg. The platform was calibrated according to the manufacturer recommendations. A CMJ-1L was performed before the 2-leg countermovement jump (CMJ-2L). Subjects performed 2 trials interspersed by 1-minute recovery for each kind of jump. For CMJ-2L, Nedelec et al[15] found a high reliability. The typical error was 1.5 cm, the intraclass correlation coefficient (ICC) .92, and the coefficient of variation (CV) 2.9%. Test–retest reliability of CMJ-1L is presented in Table 1. The typical error was 0.85 cm (90% confidence interval [CI] = 0.5–2.5), the ICC .97 (90% CI = .8–.99) and the CV 9.4%. CMJ-1L and CMJ-2L were assessed immediately postexercise (0 h), then at 24, 48, and 72 hours postexercise.

Creatine Kinase. Blood samples were taken from 32-μL fingertip capillary punctures to assess plasma creatine kinase concentration ([CK]). Blood was placed on a measurement strip, and analyses were done using a Reflotron (Roche Diagnostics, Grenzacherstrasse, Switzerland). The Reflotron was calibrated according to the manufacturer recommendations. Previous work by Horder et al[16] showed a between-days CV of 4.2% for [CK] measures with the Reflotron. Plasma [CK] was measured before exercise, then at 24, 48, and 72 hours postexercise.

Muscle Soreness and Perceived Recovery. Subjects were asked to rate their level of perceived hamstring muscle soreness using a Likert scale from 0 (not sore) to 10 (very, very sore).[17] Subjects rated their level of perceived recovery using a recovery scale from 0 (very well recovered) to 10 (very poorly recovered). The scale used here was adapted from Laurent et al,[18] who established this scale, but with an inverse number order (ie, 0 was very poorly recovered). The numbers were changed here to achieve coherence between the recovery and soreness scales (ie, from positive to negative perception). Muscle soreness was rated preexercise, immediately postexercise (0 h: before the recovery session), then 24, 48, and 72 hours after exercise. Perceived recovery was rated immediately postexercise (0 h: after the recovery session), then 24, 48, and 72 hours after exercise.

International Journal of Sports Physiology and Performance 2017.12:402-409.

Statistical Analysis

Data are presented as mean ± SD. Values for force, CMJ-1L, CMJ-2L, and [CK] were normalized to 100%. A small effect size was found for the difference of the baseline values between CWI and WBC for all outcomes. The effect of time and the effect of condition on the dependent variables—force, CMJ-1L, CMJ-2L, [CK], soreness, and perceived recovery—were analyzed using the following criteria: ≥0 to ≤0.2 = trivial, 0.21 to ≤0.6 = small, 0.61 to ≤1.2 = moderate, 1.21 to ≤2 = large, 2.1 to ≤4 = very large, and ≥4 = nearly perfect.[19] To calculate the effect size, the mean difference was defined as CWI value – WBC value for all the outcomes. CI was set at 90%. Probability to have a higher effect of a condition compared with the other was assessed qualitatively as follows: <0.5%, most unlikely or almost certainly not; 0.5% to 5%, very unlikely; 5.1% to 25%, unlikely or probably not; 25.1% to 75%, possibly; 75.1% to 95%, likely or probably; 95.1% to 99.5%, very likely; and >99.5%, most likely or almost certainly. If the probability to have results in favor of both treatments were >5%, the true difference was assessed as unclear.[20] The percentage of chance is presented in favor of CWI/trivial/WBC. For reliability of eccentric force, isometric force, and CMJ-1L the CV, ICC, 90% CIs, and typical error were calculated.[21]

Results

Rate of Perceived Exertion

A trivial effect size (–0.09; 90% CI, –0.96 to 0.79) was found for the difference of mean rating of perceived exertion collected after exercise for the CWI condition (6.3 ± 2.4) and the WBC condition (6.5 ± 2.1).

Reliability

Interday test–retest reliability for eccentric force, isometric force, and CMJ-1L was calculated. Results are presented in Table 1.

Time Effect

Effect sizes and 90% CI of each time point in comparison with baseline values are presented in Table 2 for eccentric force, isometric force, CMJ-2L, CMJ-1L, soreness, perception of recovery, and [CK] for each condition. A large to very large effect of time was found for all the outcomes across the 72 hours except CMJ-1L 72 hours postexercise and [CK] 48 hours postexercise. Figures 1 to 4 display the change over time for the different variables.

Condition Effect

Effect sizes and 90% CI of between-condition effect are presented in Figures 1 to 4. Probabilities of chances to have an effect in favor of a condition are also presented in Figures 1 to 4 for eccentric force, isometric force, CMJ-2L, CMJ-1L, soreness, perception of recovery, and [CK]. An effect of condition was found in favor of CWI for CMJ-1L and CMJ-2L 72 hours postexercise (Figure 2), muscle soreness 48 hours postexercise, and perceived recovery 24 hours postexercise (Figure 3). [CK] was largely and moderately lowered in the CWI condition in comparison with the WBC condition 24 and 72 hours after exercise, respectively.

Discussion

The aim of this study was to compare the effects of CWI and WBC on recovery kinetics after exercise-induced muscle damage. Results showed that, in comparison with WBC, a very likely moderate effect in favor of CWI was evident for accelerating CMJ-1L and CMJ-2L recovery 72 hours after exercise. In addition, a likely moderate effect in favor of CWI was found for lower muscle soreness 48 hours after exercise and better perceived recovery 24 hours after exercise. A very likely large effect and a likely moderate effect in favor of CWI were found for lower [CK] 24 and 72 hours after exercise, respectively. For eccentric and isometric force development the effect was unclear across 72 hours of recovery.

For this experiment to be useful, it was important to establish that the exercise task chosen did induce significant muscle damage. Muscle force loss is considered to be one of the best tools for quantifying muscle damage.[22] The results confirm the effectiveness of the chosen exercise task, as large to very large effects of time in both conditions were reported in force decrement (Table 2). Height of CMJ-2L was also affected by the exercise in both recovery conditions, as large to very large effects of time were found. This effect

Table 2 Time Effect of Each Outcome in Comparison With Baseline Value

Outcome	Condition	0 h	24 h	48 h	72 h
Eccentric force 60°/s (N/m)	CWI	–1.38 (–2.2 to –0.6)	–1.97 (–2.9 to –1.1)	–3.64 (–4.8 to –2.5)	–2.79 (–3.8 to –1.9)
	WBC	–1.84 (–2.7 to –1)	–1.91 (–2.8– to –1)	–2.23 (–3.2 to –1.3)	–1.51 (–2.3 to –0.7)
Isometric force 60° (N)	CWI	–4.29 (–5.6 to –3)	–2.71 (–3.7 to –1.7)	–2.8 (–3.8 to –1.8)	–2.79 (–3.8 to –1.8)
	WBC	–3.57 (–4.7 to –2.4)	–2.82 (–3.8 to –1.8)	–2.58 (–3.6 to –1.6)	–2.15 (–3.1 to –1.2)
CMJ-2L (cm)	CWI	–1.47 (–2.3 to –0.7)	–1.72 (–2 to –0.9)	–2.14 (–3.1 to –1.2)	–1.56 (–2.4 to –0.7)
	WBC	–1.25 (–2.1 to –0.5)	–1.69 (–2.5 to –1)	–1.43 (–2.3 to –0.6)	–1.57 (–2.4 to –0.7)
CMJ-1L (cm)	CWI	–1.34 (–2.1 to –0.5)	–1.03 (–1.8 to –0.3)	–1.16 (–2 to –0.4)	–0.53 (–1.3 to 0.2)
	WBC	–1.03 (–1.8 to –0.3)	–0.81 (–1.6 to –0)	–1.7 (–2.6 to –0.9)	–1.02 (–1.8 to –0.3)
[CK] (U/L)	CWI	N/A	1.33 (0.5–2.1)	0.8 (0.04–1.6)	1.67 (0.8–2.5)
	WBC	N/A	2.68 (1.7–3.7)	1.17 (0.4–2)	1.53 (0.7–2.4)
Soreness (AU)	CWI	2.15 (1.2 to 3.1)	2.35 (1.4–3.3)	3.86 (2.7–5.1)	2.88 (1.9–3.9)
	WBC	2.18 (1.3 to 3.1)	3.7 (2.5–4.9)	5.88 (4.2–7.5)	3.17 (2.1–4.3)
Perception of recovery (AU)	CWI	N/A	0.79 (0–1.6)	1.88 (1–2.8)	1.51 (0.7–2.3)
	WBC	N/A	0.99 (0.2–1.8)	1.61 (0.8–2.5)	1.33 (0.5–2.1)

Note: Data are shown as ES (90% CI). The table presents a comparison of each time point mean value with baseline values in each condition. The information given is the time effect of the exercise. The effect sizes and confidence intervals represent the difference between a given time point and the baseline value for the considered outcome.

Abbreviations: AU, arbitrary units; CI, confidence interval; [CK], creatine kinase concentration; CMJ-1L, single-leg countermovement jump; CMJ-2L, 2-leg countermovement jump, CWI, cold-water immersion; ES, effect size; WBC, whole-body cryotherapy.

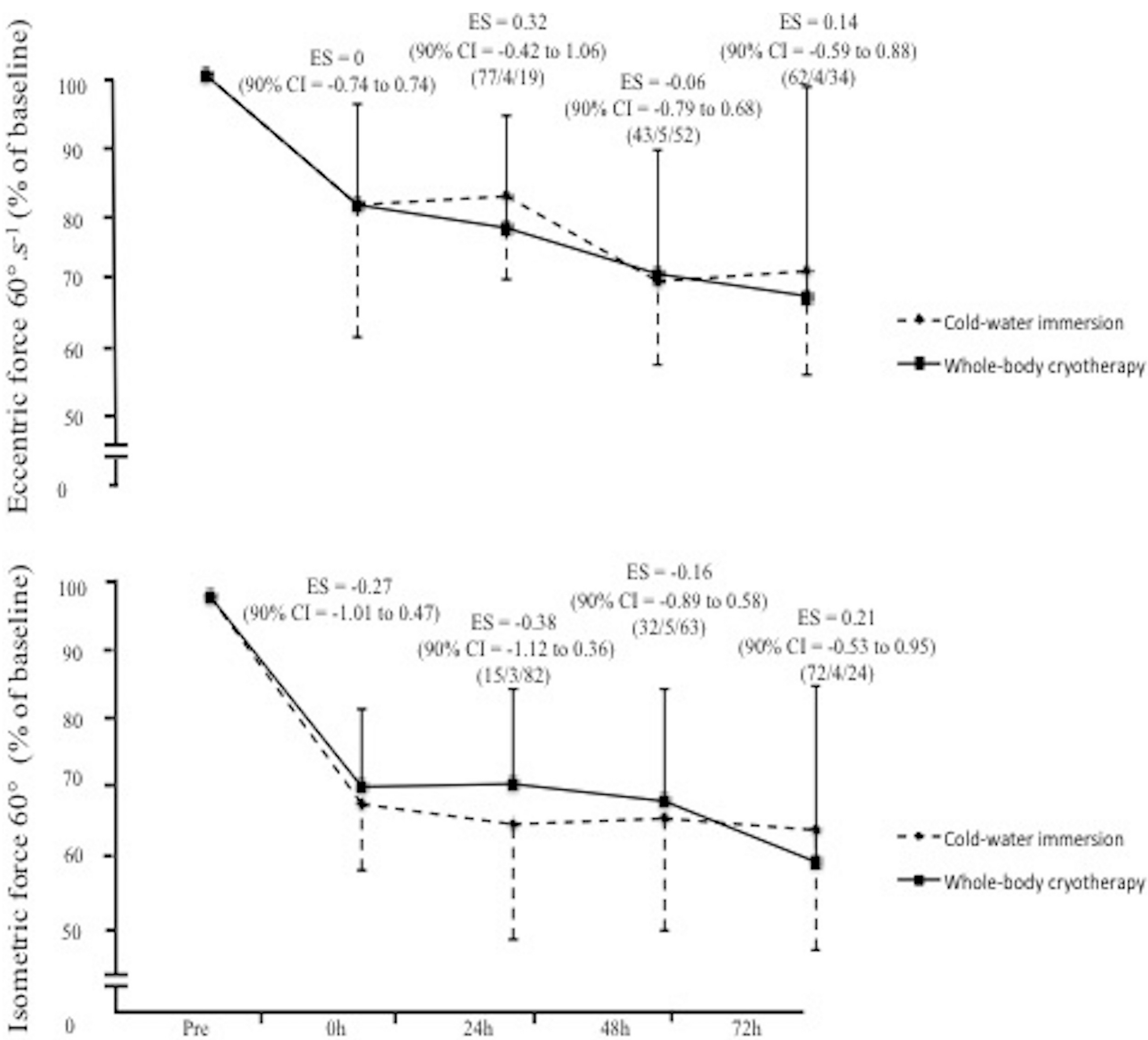

Figure 1 — Time evolution of eccentric force at 60°/s and isometric force at 60° in the cold-water immersion and whole-body cryotherapy conditions at baseline (Pre); immediately after (0 h); and 24, 48, and 72 hours after the exercise-induced muscle damage. Probabilities to have an effect are presented as (cold-water immersion/trivial/whole-body cryotherapy). Abbreviation: ES, effect size between cold-water and whole-body cryotherapy.

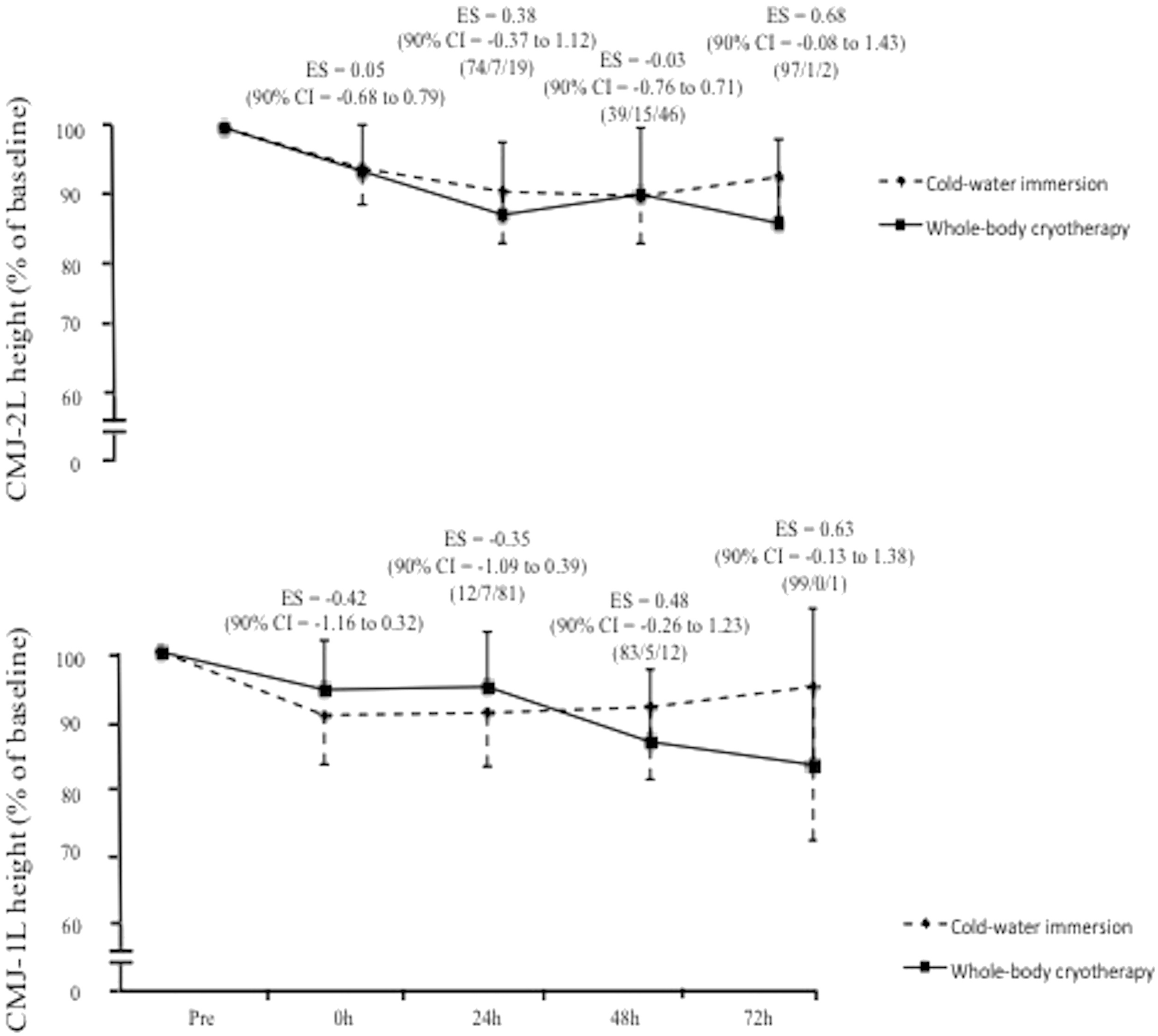

Figure 2 — Time evolution of single-leg countermovement jump (CMJ-1L) and 2-leg countermovement jump (CMJ-2L) in the cold-water immersion and whole-body cryotherapy conditions at baseline (Pre); immediately after (0 h); and 24, 48, and 72 hours after the exercise-induced muscle damage. Probabilities to have an effect are presented as (cold-water immersion/trivial/whole-body cryotherapy). Abbreviation: ES, effect size between cold-water and whole-body cryotherapy.

was less pronounced in single-leg jumps, as a moderate time effect was detected for CMJ-1L across the 72-hour postexercise recovery period in the WBC condition and moderate to large time effects only up to 48 hours postexercise in the CWI condition. Nevertheless, sufficiently high force and jump performance decrements were noted across 72 hours of recovery, to allow an assessment of the effectiveness of the 2 recovery procedures.

When comparing the conditions, CWI was found more likely to improve recovery kinetics of CMJ-1L and CMJ-2L at 72-hours postexercise. Muscle power recovery assessed from CMJ-1L and CMJ-2L was faster after CWI than WBC. The larger effect of CWI on recovery kinetics could be partly explained by the rate of heat transfer (Q). Water (0.58 W/[m – K]) has a 24.2 times higher heat-transfer coefficient (k) than air (0.024 W/[m – K]): As such, water is more efficient for extracting heat energy from the body than air.[23] In further contrast to cold air, cold water exerts a hydrostatic pressure on the body.[2] Previous work has found that CWI and hot-water immersion are both effective in improving muscle strength recovery in comparison with passive recovery, but CWI is more effective than hot-water immersion.[24] Together, these data indicate that the combination of cold and hydrostatic pressure may act together to improve performance recovery kinetics. It can be hypothesized that the faster recovery kinetics with CWI may be at least partially linked with the capacity of water to extract heat combined with the hydrostatic pressure. CWI is more effective than hot-water immersion in accelerating muscle recovery,[24] indicating that cold may be a factor that accelerates muscle recovery. Water has a higher heat-transfer coefficient than air),[23] and CWI may decrease skin temperature for a longer duration than WBC. As recovery kinetics of muscular force was not different between CWI and WBC, one can suggest that CWI enhanced speed recovery faster than WBC.

WBC and CWI have both demonstrated the ability to decrease muscle soreness across 72 hours postexercise.[6,25] The results suggest that CWI was more effective in decreasing muscle soreness

International Journal of Sports Physiology and Performance 2017.12:402-409.

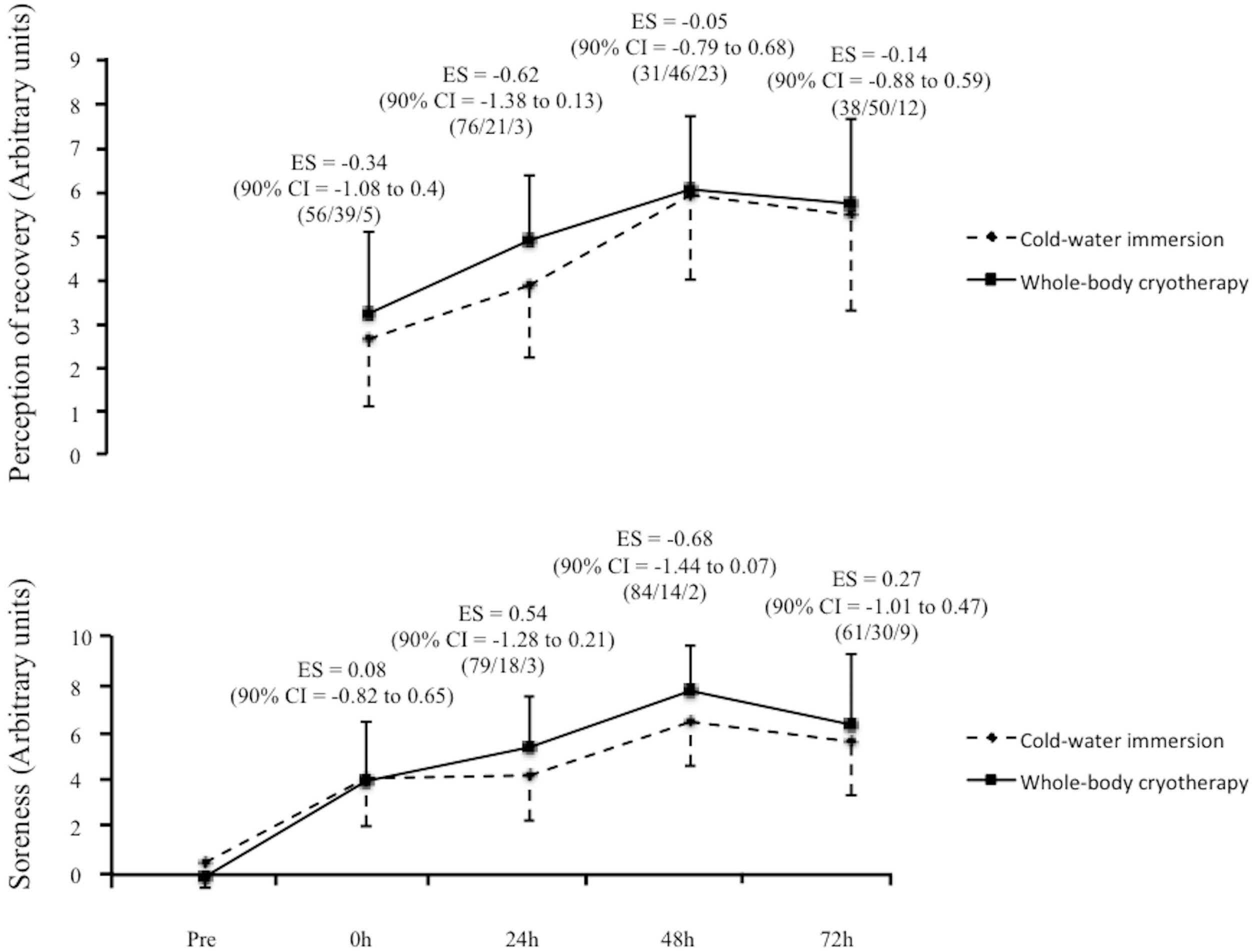

Figure 3 — Time evolution of muscle soreness and perception of recovery in the cold-water immersion and whole-body cryotherapy conditions at baseline (Pre); immediately after (0 h); and 24, 48, and 72 hours after the exercise-induced muscle damage. Probabilities to have an effect are presented as (cold-water immersion/trivial/whole-body cryotherapy). Abbreviation: ES, effect size between cold-water and whole-body cryotherapy.

at 48 hours postexercise and that perceived recovery was higher at 24 hours after exercise. These findings are consistent with a recent meta-analysis[6] that reported a lower general fatigue after exercise for subjects using CWI in comparison with passive recovery. With regard to potential mechanisms, Algafly and George[26] found that pain threshold and pain tolerance were increased and nerve conduction velocity of the tibial nerve was reduced after direct ice application on the ankle. Applying pressure with compression garments to muscles has also been shown to decrease perceived muscle soreness.[27] As cold water can decrease skin temperature for a longer period than air[28] and also exerts a pressure on the body,[2] it can be hypothesized that this longer temperature decrease combined with the pressure exerted by water may have also increased pain tolerance.

Similar to other studies,[7] [CK] increased after the muscle damaging exercise. A large effect of time was found 24 and 72 hours postexercise and a moderate effect of time was found 48 hours postexercise in the CWI condition. Very large and large effects were found at 24, 48 and 72 hours postexercise, respectively, in the WBC condition. For the condition effect, a very likely large effect and a likely moderate effect in favor of CWI, respectively, 24 and 72 hours postexercise, suggesting a higher effectiveness of CWI in comparison with WBC.

Limitations

This study presents some limitations. First, the sample size was too small for some of the variables studied. A statistical power test was performed, retrospectively, for the following variables: eccentric force (power = 1), isometric force (power = 1), CMJ-1L (power = 0.18), and CMJ-2L (power = 0.35). Second, due to the crossover design and the fact that subjects performed a single-leg exercise, it was not possible to implement a true control condition. Having a control condition would have allowed an analysis of the efficiency of each recovery procedure in comparison with a passive recovery. Third, muscle and skin temperatures were not measured in this study and may have provided useful information on the heat exchange afforded by each recovery procedure. According to the study of Costello et al,[28] who compared vastus lateralis and thigh skin temperature decrease between CWI (4 min at 8°C) and WBC (20 s at –60°C and 3 min and 40 s at –110°C), a 2°C-drop in muscle temperature (3 cm below the subcutaneous fat layer) can be expected 60 minutes after exposure in both conditions. In the CWI condition, a 9°C drop in skin temperature can be expected immediately after exposure and a 5°C drop can be expected 60 minutes after exposure. In the WBC condition, a 12°C drop can be expected immediately after exposure and a 4°C drop can be expected

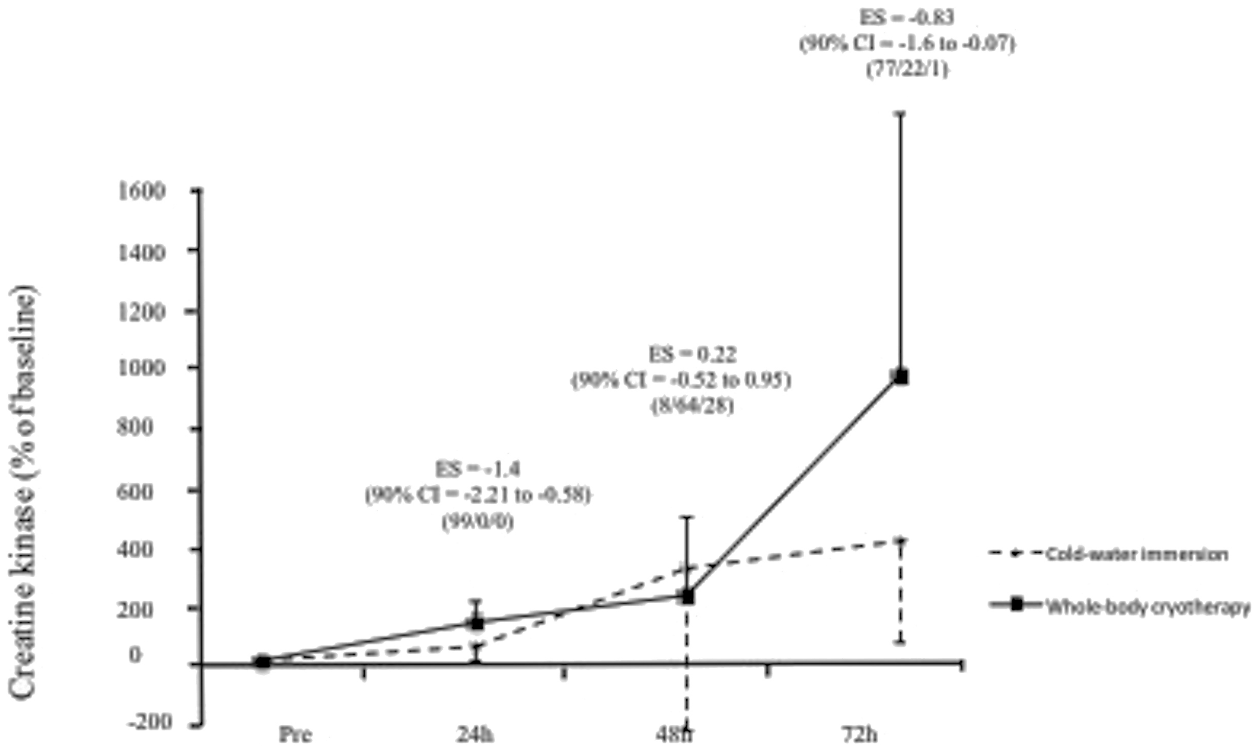

Figure 4 — Time-evolution of creatine kinase concentrations in the cold-water immersion and whole-body cryotherapy conditions at baseline (Pre) and 24, 48, and 72 hours after the exercise-induced muscle damage. Probabilities to have an effect are presented as (cold-water immersion/trivial/whole-body cryotherapy). Abbreviation: ES, effect size between cold-water and whole-body cryotherapy.

60 minutes after exposure. The amplitude of CIs obtained for force were very large, spanning all levels of magnitude and potentially leading to unclear results.[20]

Practical Applications

This study shows that, in this hamstring-damaging protocol, using CWI was more beneficial than WBC to improve muscle power recovery 72 hours after the exercise. Implementing CWI is a potentially useful strategy to accelerate recovery after an exercise-inducing muscle damage.

Conclusion

To our knowledge this study is the first to directly compare CWI and WBC effects on performance recovery after exercise-induced muscle damage. The results showed that CWI may be more efficient in accelerating recovery kinetics than WBC for CMJ-1L and CMJ-2L at 72 hours postexercise. Although no differences in strength recovery were found between the 2 procedures, CWI did lower ratings of muscle soreness and increase perceived recovery across 24 to 48 hours postexercise. In perspective, it would be interesting to study the effects of both strategies for repeated treatments at 24 and 48 hours postexercise on recovery kinetics and the repeated bout effect.

Acknowledgments

The authors gratefully acknowledge all the subjects who participated in this study.

References

1. Nédélec M, McCall A, Carling C, Legall F, Berthoin S, Dupont G. Recovery in soccer: part II-recovery strategies. *Sports Med*. 2013a;43(1):9–22. PubMed doi:10.1007/s40279-012-0002-0
2. Wilcock IM, Cronin JB, Hing WA. Physiological response to water immersion: a method for sport recovery? *Sports Med*. 2006;36(9):747–765. PubMed doi:10.2165/00007256-200636090-00003
3. Banfi G, Lombardi G, Colombini A, Melegati G. Whole-body cryotherapy in athletes. *Sports Med*. 2010;40(6):509–517. PubMed doi:10.2165/11531940-000000000-00000
4. Clarkson PM, Hubal MJ. Exercise-induced muscle damage in humans. *Am J Phys Med Rehabil*. 2002;81(11 Suppl):S52–S69. PubMed doi:10.1097/00002060-200211001-00007
5. Versey NG, Halson SL, Dawson BT. Water immersion recovery for athletes: effect on exercise performance and practical recommendations. *Sports Med*. 2013;43(11):1101–1130. PubMed doi:10.1007/s40279-013-0063-8
6. Bleakley C, McDonough S, Gardner E, Baxter GD, Hopkins JT, Davison GW. Cold-water immersion (cryotherapy) for preventing and treating muscle soreness after exercise. *Cochrane Database Syst Rev*. 2012;15(2):CD008262.
7. Hausswirth C, Louis J, Bieuzen F, et al. Effects of whole-body cryotherapy vs. far-infrared vs. passive modalities on recovery from exercise-induced muscle damage in highly-trained runners. *PLoS One*. 2011;6(12):e27749. PubMed doi:10.1371/journal.pone.0027749
8. Ferreira-Junior JB, Bottaro M, Vieira A, et al. One session of partial-body cryotherapy (-110 °C) improves muscle damage recovery. *Scand J Med Sci Sports*. 2015;25(5):e524–e530. PubMed doi:10.1111/sms.12353

9. 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. PubMed doi:10.1136/bjsports-2011-090061
10. Roberts LA, Raastad T, Markworth JF, et al. Post-exercise cold water immersion attenuates acute anabolic signalling and long-term adaptations in muscle to strength training. *J Physiol*. 2015;593(18):4285–4301. PubMed doi:10.1113/JP270570
11. Poppendieck W, Faude O, Wegmann M, Meyer T. Cooling and performance recovery of trained athletes: a meta-analytical review. *Int J Sports Physiol Perform*. 2013;8(3):227–242. PubMed doi:10.1123/ijspp.8.3.227
12. Bailey DM, Erith SJ, Griffin PJ, et al. Influence of cold-water immersion on indices of muscle damage following prolonged intermittent shuttle running. *J Sports Sci*. 2007;25(11):1163–1170. PubMed doi:10.1080/02640410600982659
13. Starbuck C, Eston RG. Exercise-induced muscle damage and the repeated bout effect: evidence for cross transfer. *Eur J Appl Physiol*. 2012;112(3):1005–1013. PubMed doi:10.1007/s00421-011-2053-6
14. Foster C, Florhaug JA, Franklin J, et al. A new approach to monitoring exercise training. *J Strength Cond Res*. 2001;15(1):109–115. PubMed
15. Nédélec M, McCall A, Carling C, Le Gall F, Berthoin S, Dupont G. Physical performance and subjective ratings after a soccer-specific exercise simulation: comparison of natural grass versus artificial turf. *J Sports Sci*. 2013b;31(5):529–536. PubMed doi:10.1080/02640414.2012.738923
16. Hørder M, Jørgensen PJ, Hafkenscheid JC, et al. Creatine kinase determination: a European evaluation of the creatine kinase determination in serum, plasma and whole blood with the Reflotron system. *Eur J Clin Chem Clin Biochem*. 1991;29(10):691–696. PubMed
17. Thompson D, Nicholas CW, Williams C. Muscular soreness following prolonged intermittent high-intensity shuttle running. *J Sports Sci*. 1999;17(5):387–395. PubMed doi:10.1080/026404199365902
18. Laurent CM, Green JM, Bishop PA, et al. A practical approach to monitoring recovery: development of a perceived recovery status scale. *J Strength Cond Res*. 2011;25(3):620–628. PubMed doi:10.1519/JSC.0b013e3181c69ec6
19. Hopkins WG. A scale of magnitudes for effect statistics. In: *A New View of Statistics*. 2002a. http://www.sportsci.org/resource/stats/effectmag.html. Accessed April 15, 2015.
20. Batterham AM, Hopkins WG. Making meaningful inferences about magnitudes. *Int J Sports Physiol Perform*. 2006;1(1):50–57. PubMed doi:10.1123/ijspp.1.1.50
21. Hopkins WG. Precision of measurement. In: *A New Vew of Statistics*. 2002b. http://www.sportsci.org/resource/stats/precision.html. Accessed April 15, 2015.
22. Warren GL, Lowe DA, Armstrong RB. Measurement tools used in the study of eccentric contraction-induced injury. *Sports Med*. 1999;27(1):43–59. PubMed doi:10.2165/00007256-199927010-00004
23. Bleakley CM, Bieuzen F, Davison GW, Costello JT. Whole-body cryotherapy: empirical evidence and theoretical perspectives. *Open Access J Sports Med*. 2014;5:25–36. PubMed doi:10.2147/OAJSM.S41655
24. Vaile J, Halson S, Gill N, Dawson B. Effect of hydrotherapy on the signs and symptoms of delayed onset muscle soreness. *Eur J Appl Physiol*. 2008;102(4):447–455. PubMed doi:10.1007/s00421-007-0605-6
25. Costello JT, Baker PR, Minett GM, Bieuzen F, Stewart IB, Bleakley C. Whole-body cryotherapy (extreme cold air exposure) for preventing and treating muscle soreness after exercise in adults. *Cochrane Database Syst Rev.* 2015;18(9):CD010789.
26. Algafly AA, George KP. The effect of cryotherapy on nerve conduction velocity, pain threshold and pain tolerance. *Br J Sports Med*. 2007;41(6):365–369. PubMed doi:10.1136/bjsm.2006.031237
27. Hill J, Howatson G, van Someren K, Leeder J, Pedlar C. Compression garments and recovery from exercise-induced muscle damage: a meta-analysis. *Br J Sports Med*. 2014;48(18):1340–1346. PubMed doi:10.1136/bjsports-2013-092456
28. Costello JT, Culligan K, Selfe J, Donnelly AE. Muscle, skin and core temperature after –110°C cold air and 8°C water treatment. *PLoS One*. 2012;7(11):e48190. PubMed doi:10.1371/journal.pone.0048190