Differential effects of post-exercise ice water immersion and room temperature water immersion on muscular performance, vertical jump, and agility in amateur rugby players: A randomized controlled trial

Effets différentiels de l'immersion post-exercice en eau glacée et en eau à température ambiante, sur la performance musculaire, le saut vertical et l'agilité chez les joueurs de rugby amateurs: Essai réalisé au hasard

Short title: Effects of varied temperature water immersion on performance

G.C.C. Chow[a,b], J.W.Y. Chung[c], S.S.M. Fong[a,*]

[a] School of Public Health, Li Ka Shing Faculty of Medicine, The University of Hong Kong, Hong Kong

[b] Faculty of Liberal Arts and Social Sciences, The Education University of Hong Kong, Hong Kong

[c] Department of Health and Physical Education, The Education University of Hong Kong, Hong Kong

*** Corresponding author:**

Dr. Shirley S.M. Fong

School of Public Health, Li Ka Shing Faculty of Medicine,

The University of Hong Kong, Pokfulam, Hong Kong

E-mail: smfong@hku.hk

Tel.: (852)28315260

Fax: (852)28551712

Word count (excluding abstract and references): 3685 (23918 characters with spaces)

Abstract word count: 184 (English); 236 (French)

Number of tables: 2

Number of figures: 1

Summary

Objective.– This study compared the effects of post-exercise water immersion at different temperatures on the muscular and functional performance in rugby players.

Methods. – Fifty-three participants (21.6 ± 2.9 years) were randomly assigned to an ice water immersion (IWI; 5℃) group, a room temperature water immersion (RWI; 25℃) group, or a no-immersion group. After a bout of fatiguing exercise, the participants underwent an immersion intervention. The outcomes were measured at baseline and post-intervention. The isokinetic peak torque and time to peak torque during knee extension and flexion at 60°/s were recorded, along with countermovement jump height and the time taken to complete a hexagon agility test.

Results. – There were significant group-by-time interaction effect ($P < 0.001$) and time effect ($P < 0.001$) in the time to peak torque of knee flexion. RWI helped the rugby players' knee muscles to reach peak torque more quickly, whereas IWI impaired both knee extensor peak force and jump performance. The agility test outcome improved on the post-test in all groups. Post-exercise IWI harmed both the knee muscular and jump performance, whereas RWI improved performance of the knee muscles.

Résumé

Objectifs. – Cette étude a comparé les effets de l'immersion post-exercice, dans une eau à différentes températures, sur la performance musculaire et fonctionnelle des joueurs de rugby.

Méthode. – Cinquante-trois participants (21.6 ± 2.9 ans) ont été répartis au hasard dans un groupe d'immersion en eau glacée (IWI; 5℃), un groupe d'immersion en eau a température ambiante (RWI; 25℃) et un groupe sans immersion. Après un exercice fatiguant, les participants ont été immerges. Les résultats ont été mesurés à la ligne de base et après l'intervention. Le couple maximal isocinétique et le couple horaire à pic pendant l'extension du genou et la flexion à 60°/s ont été enregistrés, ainsi que la hauteur de saut du contre-mouvement et le temps nécessaire pour compléter un test d'agilité hexagonale.

Résultats. – Il y a eu un effet d'interaction groupe par temps significatif ($P < 0.001$) et un effet de temps ($P < 0.001$) dans le couple horaire à pic de flexion du genou. IWI a aidé les muscles du genou des joueurs de rugby à atteindre le couple maximal plus rapidement, tandis que RWI a altéré la force maximale des extenseurs du genou et les performances de saut. Le résultat du test d'agilité est meilleur dans le test après intervention dans tous les groupes. L' IWI postérieure à l'exercice a diminué à la fois les performances du genou musculaire et du saut, alors que RWI a amélioré les performances des muscles du genou.

Keywords: immersion, temperature, rugby, muscle

1. Introduction

Recovery is a challenge for rugby sevens players, who often undertake multiple competitions in a single day and perform in matches on consecutive days. High-performance athletes are expected to maintain a high level of performance throughout their packed competition schedules. Between matches, however, the body needs to adapt to physiological stress. Fatigue has been shown to cause variation in running intensity [1], to reduce performance in repeated high-intensity activities [2], and to impede acceleration [3]. In a study, substantial deficits in performance were consistently observed during the last 3 minutes of every match [4]. Although athletes at different levels may differ in their physical and technical performance, the overall demands of matches are fairly similar [5]. In a competition scenario with a limited recovery time between matches, the quality of recovery is vital to athletic success. An optimal recovery can provide various benefits during repeated intense physical exertion. Therefore, it is important to examine the effectiveness of different recovery interventions and their influence on the crucial factors that affect sports performance.

Post-exercise water immersion has been widely accepted as an effective on-field recovery strategy: it is generally believed to speed up recovery to prepare athletes for another round of competition. Athletes have usually reported a reduction in muscle soreness after post-exercise water immersion at low temperature [6]. Some studies have also indicated that water immersion at low temperature helps to restore maximal voluntary muscle contraction, central activation, and motor-unit recruitment after repeated sprinting [7,8]. However, the recovery effect of water immersion on human skeletal muscle fibers is highly dependent on temperature [9], which can affect motor and sensory neural conductivity in different ways [10–12].

According to Robertson, Ward, Low, and Reed [13], athletes immersed in ice water usually feel cold or even experience pain (at water temperature of 5℃ to 10℃), but feel comfortable when immersed in water at room temperature (from 15℃ to 25℃). However, on-field practitioners tend to use extremely cold water for immersion to compensate for athletes' limited recovery time. The cooling effect is the major effect proposed in water immersion at low water temperatures [14]. Therefore, it is logically sound and technically easier to use room temperature water immersion (RWI) at 25℃ (a comfortable water temperature that is lower than body temperature) to replace ice water immersion. To the best of our knowledge, no previous scholars have attempted to determine whether immersion in painfully cold water is necessary for post-exercise recovery to improve sporting performance. Therefore, the purpose of this study was to compare the effects of post-exercise ice water immersion (IWI), room temperature water immersion (RWI), and no water immersion on the muscular performance and functional performance (vertical jumping and agility) of rugby players.

2. Methods

2.1. Study design

The study was an assessor-blinded, three-armed randomized controlled trial. The study protocol was approved by the Human Research Ethics Committee of the University of Hong Kong. All participants gave written informed consent before participation. The experimental procedures were in line with the Declaration of Helsinki.

2.2. Participants

Amateur rugby players were recruited through poster and online advertising and by contacting the coaches of local recreational and university rugby clubs (Table 1). The inclusion criteria were (1) age 18 to 35 years, (2) participation in regular rugby training (>3 $h \cdot wk^{-1}$), and (3) a minimum of 1 year of training experience. The exclusion criteria were (1) serious injury within the past 12 months that may affect test performance, (2) a significant musculoskeletal, cardiovascular, neurological, cognitive, visual, vestibular, or other sensorimotor disorder, (3) muscle fatigue on the day of assessment, (4) cold sensitivity, (5) an open wound or a dermatological or infectious disease, (6) menstruation in female participants, and (7) incontinence.

2.3. Screening and randomization

A sports scientist blinded to the group allocation screened the participants and carried out the assessment. An independent research assistant carried out the randomization procedure (using random allocation cards and sealed opaque envelopes to ensure concealed allocation). The eligible participants were randomly assigned to one of three groups: an IWI group, an RWI group, and a control group. Another trained research assistant provided support for the IWI and RWI interventions.

2.4. Interventions

Phase 1 – fatiguing protocol. All participants were invited to run on a high-performance motorized treadmill set at a 1.0% gradient while wearing a safety harness to prevent falls. To familiarize the participants with the fatiguing protocol, a 5-min warm-up session was included. The participants performed five sub-maximal sprints for 5 s each on the treadmill and took a 1-min break. Next, a fatiguing protocol was performed, comprising 14 sprints of 15 s each, with rest intervals of 45 s. High-intensity running was chosen for the fatiguing protocol to exert stress on the participants' cardiovascular and muscular systems and to exhaust their aerobic-energy systems. The participants wore heart rate monitors (Polar Electro Oy, Kempele, Finland) to obtain continuous heart rate measurements and were asked to report their rate of perceived exertion (RPE) after each sprint. A certified strength and conditioning specialist adjusted the treadmill speed according to the participants' heart rate responses during sprinting to ensure that the participant reached 90% of their maximal oxygen consumption [15]. The participants received verbal encouragement throughout the fatiguing exercise.

Phase 2 – recovery intervention. A 1-min recovery intervention was performed immediately after the fatiguing exercise. This short period was chosen for the recovery intervention because it reflected common on-field practice due to the limited time between matches [14]. The participants in the two intervention groups wore swimming shorts/suits in preparation for the water immersion recovery intervention. The participants allocated to the IWI group stood in a tank filled with ice water at 5℃ for 1 minute, with the water level reaching the iliac crest. The water temperature was monitored using a digital thermometer (TPI-326, Test Products International Inc., Beaverton, OR; accuracy: ±1℃) and adjusted if necessary by adding crushed ice. The participants allocated to the RWI group underwent immersion in tap water (25℃) in the same tank, with the same procedures followed. The participants allocated to the control group sat on chairs in the laboratory for 1 minute and did not undergo water immersion. Cold perception during recovery was assessed using a visual analog scale of thermal strain (ranged from 0: unbearably cold to 10: unbearably hot; 5 is neutral). All interventions were performed in a temperature-controlled laboratory (25℃; relative humidity, 75%).

2.5. Test procedures

The data collection was conducted by a blinded assessor in the Human Performance Laboratory at the Education University of Hong Kong. The outcomes including isokinetic muscle strength and speed of muscle contraction, vertical jump height, and agility were measured in a random order before the intervention (pre-test) and immediately afterward (post-test). Restoration of these motor and functional performances after fatiguing exercise was used to evaluate and compare the efficiency of the two recovery strategies (IWI and RWI).

2.5.1. Primary outcome – muscular performance

The muscular performance of the dominant knee was measured with an isokinetic dynamometer (Cybex NORM, Humac, CA). Each participant was positioned on an adjustable chair and secured to the machine with straps across the trunk, hips (flexed to 85°), and thighs. The knee-joint axis (defined as the lateral epicondyle of the femur) was in line with the rotational axis of the dynamometer. The testing range of motion was full knee extension-flexion, and the testing velocity was 60°/s. The gravity-compensation and testing procedures were performed according to the manufacturer's instructions [16]. After a familiarization trial comprising five submaximal knee extension-flexion movements, the participants were asked to complete three continuous maximal knee extension-flexion movements as a test ensemble.

Verbal encouragement was given throughout the tests. The average body weight-adjusted concentric isokinetic peak torque ($N \cdot m \cdot kg^{-1}$) and time to peak torque (s) measured in the three trials of both knee extension and flexion were used for analysis. Isokinetic knee muscle testing (interclass correlation coefficient [ICC], 0.93 to 0.98) has been reported to be highly reliable [17].

2.5.2.Secondary outcomes—vertical jump and agility performance

Vertical countermovement jumps (CMJs) were measured using a contact/pressure mat (Fitness Technology, Kinematic Measurement System, Australia). The participants began by standing with both feet flat on the contact mat with their hands on their hips to prevent the influence of arm movements on vertical jumping performance. Next, they were instructed to squat (to a knee flexion of approximately 120°) as quickly as possible and then to jump upward as high as possible (concentric phase). The participants took off with their knees in extension and their ankles in plantar flexion and landed in a similarly extended posture. After a familiarization trial (two submaximal CMJs), each participant performed three CMJs with maximal effort. A 5 s break was allowed between jumps. The best jump (i.e., the greatest height) was chosen for analysis. The test-retest reliability of the CMJ test is very high (ICC, 0.98) [18].

To test the participants' agility, a hexagon agility test was performed. Each participant was invited to stand facing forward on a standardized mat displaying an image of a hexagon. The participants stood in the center of the hexagon and were required to perform a double-leg hop over each sideline and back in a continuous clockwise sequence until they had navigated around the hexagon three times. A stopwatch was used to record the time taken for each trial. The stopwatch was started when the participants began their hop over the first sideline and stopped when they returned to the center mark on the last hop. The participants' performance was not recorded if they failed to jump over one or more sidelines completely; in this case, they were required to repeat the test. The participants were instructed to complete the test as quickly as possible. After five submaximal familiarization trials, the participants performed three all-out trials with 1-min rest intervals. The fastest trial was used for analysis. The hexagon agility test has been shown to have excellent test-retest reliability (ICC, 0.938) for assessment of athletic performance and agility [19].

2.6. Statistical analysis

The sample size was estimated using the G*Power software package (version 3.1.0, Franz Faul, University of Kiel, Germany). According to a meta-analysis by Leeder and his colleagues in 2012 [20], the improvement to the muscular power of healthy adults resulting from post-exercise water immersion at low temperature has an effect size of 0.597. In the current study, assuming a two-tailed alpha level of 0.05 and statistical power of 0.80 (pre- and post-intervention measurements with three groups), the minimum sample size required was 12 per group or 36 participants in total. We did not anticipate dropouts because the pre- and post-intervention measurements were all taken during a single visit.

The statistical analysis was conducted using the SPSS 21.0 software package (IBM, Armonk, NY). Descriptive statistics (e.g., mean and standard deviation) were obtained for all data. The Shapiro-Wilk test and/or histograms were used to check the normality of the data. Differences between groups in the participants' baseline characteristics were calculated using one-way analysis of variance for continuous data or the chi-square test for categorical data. If a significant statistical difference was found, the potential confounder was added to the subsequent analysis as a covariate. In addition, the analysis was based on the intention to treat assumption, specifically, the last observation carried forward assumption.

The overall effects of the interventions on performance as measured by the primary and secondary outcomes were analyzed using two separate sets of two-way repeated-measures multivariate analyses of variance. The between-subjects factor was group, and the within-subject factor was time. Multivariate analysis was used to reduce the probability of a type I error due to multiple comparisons. Follow-up analysis was performed using a paired *t*-test, one-way analysis of variance, and/or post-hoc pairwise comparison, as appropriate. Statistical significance was set at 0.05 (two-tailed), and the Bonferroni correction method was used where necessary to maintain the overall type I error at .05. The effect size (partial eta-squared, η_p^2) was also calculated (0.01 = small effect; 0.06 = medium effect; 0.14 = large effect).

3. Results

Fifty-five amateur rugby players were screened between June 2014 and July 2015 to determine their eligibility for inclusion in the study. Two participants were excluded due to their failure to meet the inclusion criteria (one with significant musculoskeletal injury within the previous 12 months and one with high resting blood pressure). Of the 53 eligible players, 13 were randomly assigned to the IWI group, 18 to the RWI group, and 22 to the control group. The flow of the participants through the stages of the study is presented in Figure 1.

There were no significant differences between the three groups in demographic characteristics (Table 1) or outcome variables (Table 2) at baseline. None of the participants in the intervention groups dropped out, but 12 of the 22 participants (54.5%) in the control group dropped out (Figure 1). The major reasons for dropout were as follows: the belief that they could not complete the intervention (6 subjects) and a potential loss of interest in the study (6 subjects; Fig. 1).

3.1. Primary outcomes

A significant group-by-time interaction effect (F (2, 50) = 8.964; $P < 0.001$; $\eta_p^2 = 0.264$) and a significant time effect (F (1, 50) = 20.209; $P < 0.001$; $\eta_p^2 = 0.288$) were observed in the time to peak torque of knee flexion. The participants assigned to the RWI group required less time to reach peak force in their knee-flexor muscles after the intervention (23.04%; $P < 0.001$). No significant changes in the time to peak torque of knee flexion in either the IWI group or the control group were observed over time ($P > 0.05$; Table 2).

A significant time effect was also observed in the time to peak torque of knee extension (F (1, 50) = 4.954; $P = 0.031$; $\eta_p^2 = 0.090$). Post-hoc analysis revealed that only the RWI group showed a significant improvement over time (7.40%; $P = 0.012$). No significant within-group changes were detected in the IWI group or the control group ($P > 0.05$; Table 2).

Our results also reveal that the time effect on the body weight-adjusted isokinetic peak torque of knee extension was significant (F (1, 50) = 11.425; $P = 0.001$; $\eta_p^2 = 0.186$). Follow-up analysis revealed a significant decrease in the knee extensors' peak torque after the intervention in the IWI group only (−8.15%; $P = 0.018$). No significant changes were noted over time in either of the other groups ($P > 0.05$). In addition, the group, time, and group-by-time interaction effects on the body weight-adjusted isokinetic peak torque of knee flexion were not found to be significant ($P > 0.05$; Table 2).

3.2. Secondary outcomes

No significant group-by-time interaction effect ($P = 0.064$; $\eta_p^2 = 0.104$) or group effect ($P = 0.746$; $\eta_p^2 = 0.012$) on CMJ height was observed. However, the time effect was significant ($P = 0.002$; $\eta_p^2 = 0.169$). The IWI group showed a significant decrease in jump height after the intervention (−3.23%; $P = 0.030$). No significant changes in jump height were noted in either of the other groups over time ($P > 0.05$).

The time effect on the hexagon agility test time was significant ($P < 0.001$; $\eta_p^2 = 0.362$). A decrease in the agility test time (i.e., better performance) was observed after IWI (−8.92%; $P = 0.004$), after RWI (−7.96%; $P = 0.007$), and in the control group (no intervention; −4.09%; $P = 0.020$). However, neither the group-by-time interaction effect ($P = 0.168$; $\eta_p^2 = 0.069$) nor the group effect ($P = 0.263$; $\eta_p^2 = 0.052$) was significant.

3.3. Adverse events

Before the recovery intervention (IWI, RWI, or no-immersion), each participant performed repeated sprinting. The mean heart rate during exercise was 184.2 ± 8.6 beats/min, and the mean RPE was 18.7/20 ("very, very hard"). The perception of thermal strain ranged from unbearably cold to cold (mean score ± SD = 1.46 ± 0.52) in the IWI group, cold to neutral (mean score ± SD =3.61 ± 0.85) in the RWI group, and neutral (mean score ± SD =5.00 ± 1.11) in the control group. No injuries or other adverse events were reported during the interventions or assessments.

4. Discussion

In a water immersion recovery intervention after a standardized repeated sprinting session to simulate behavior in a rugby sevens tournament, our data demonstrated immediate changes in muscular and functional (jump and agility) performance relative to baseline measurements in a group of healthy amateur rugby players. The results indicate that RWI is a more effective recovery method than either IWI or no immersion. Immersion in painfully cold water [13] has no benefits beyond those of comfortable RWI.

Isokinetic strength testing revealed faster knee muscular contraction to the point of maximum torque development after 1 minute of RWI. The time to peak torque is the time taken to reach maximum torque development, which may be an indicator of explosive power [21,22]. This result is supported by previous findings regarding the effectiveness of cold-water immersion in assisting in the recovery of muscle power [20,23].

The time to peak torque of the hamstring has been found to predict 31% of the variation in sprint time at 5 m [24], which is an essential aspect of physical performance in rugby. Advanced early acceleration ability (0 to 5 m) is advantageous for skill execution during a dynamic rugby game situation. The severe cooling effected by IWI in this study impaired muscle peak force generation but generated a similar time to peak torque. The force-velocity properties of human skeletal muscle fibers are highly temperature dependent [9]. Variation in cooling intensity may explain the differences between the results for RWI and IWI. Oksa et al. [25] suggested that subnormal muscle temperature reduces muscle perfusion for a given workload. The reduction in muscle perfusion caused by severe muscle cooling – either very cold muscle cooling (5℃) or prolonged cooling (20 min) – may also reduce motor-neuron firing rates [10]. It has also been found to limit nerve conduction velocity [11] and prolong the M-wave [12].

Therefore, alterations in the muscle's ability to rapidly develop tension and reach peak force were also expected [26,27]. However, cooling of the skin with only a moderate change in muscle temperature (± 3℃) may have a different effect on neuromuscular performance [25,28]. In contrast with previous studies, we cooled muscles that may have been heated by repeated fatiguing sprints. Post-exercise RWI was found to provide a moderate temperature reduction believed to increase motor-unit recruitment [29] and the excitability of the motor-neuron pool [25]. In addition, type-II fibers are responsible for producing high levels of force, power, and speed. The cooling effect of RWI may have enhanced recovery [20] and triggered the recruitment of type-II fibers [30,31].

CMJ performance is thought to be an easily implemented but valuable indicator of muscular power, which is a key predictor of athletes' maximal speed [32,33] and explosive strength [34]. It is also a useful means of assessing the mobility and functional capacity of fatigued athletes [35]. A previous study showed that cold-water immersion (at 5℃ and 15℃) promoted the recovery of stretch shortening cycle performance in the late recovery phase (72 h after exercise) but had no immediate effect [6]. In our study, however, the parameters of jumping power were altered along with reduced muscle output after the fatiguing exercise and IWI recovery. A decline in functional power performance after exposure to severe cooling or prolonged cooling has consistently been observed as soon as 1 h after exercise and as long as 48 h after exercise [6,36]. This decline has been attributed to the exacerbated inflammatory response [37] and reduced motor and sensory neural conductivity [10–12]. Those physiological responses may also be associated with our observation of an immediate reduction in CMJ performance in the IWI group after excessive repeated sprinting and a severe cooling intervention.

Although the interaction effect was not found to be significant, all three groups completed the hexagon agility test more quickly in the post-test than in the pre-test. This finding is not consistent with the results of a standard T-test of agility conducted by Patterson and his colleagues [38], which indicated a reduction in performance immediately after recovery. A possible reason for this inconsistency is that the participants in our study used quick rebound jumps to move back and forth over the hexagon sidelines, with a restricted joint angle of the foot, knee, and hip joints. Such jumps require less involvement of the stretch-shortening cycle in the thigh muscles [36]. This may explain why the effect of cooling reported by Patterson, et al. [38] was not observed in our study. The inconsistency may also be due to the participants' cognitive involvement during the agility test. Agility is an essential element of invasion sports. It combines the ability to change direction with cognitive elements such as decision making [39]. Although familiarization trials were conducted before the main test, the learning effect may have strengthened the links between decisions and jumps and thereby improved overall performance.

The study has two major limitations. First, the control group showed a relatively high attrition rate. Intention to treat analysis was conducted based on the last observation carried forward assumption. This resulted in conservative estimates of efficacy due to effect dilution. We believe that the high dropout rate in the control group resulted primarily from the participants' disappointment in their passive resting recovery rate after an exhausting exercise protocol. Future researchers should consider allocating other common on-field recovery methods, such as active recovery, to the control group. Second, the generalizability of the study may be compromised by the use of strict inclusion criteria. Therefore, future researchers should consider recruiting a more diverse population, such as rugby players who take up different playing positions, which may be associated with different on-field exercise patterns and anthropometrics.

5. Conclusions

Compared with ice water immersion and no immersion, room temperature water immersion is the optimal post-exercise recovery method for amateur rugby players because it reduces the time taken to reach peak force in the knee muscles and may improve agility. Ice water immersion is not recommended for post-exercise recovery because it hinders maximum force generation in the knee extensor muscles and compromises jump performance.

Funding

No external financial support is declared for research.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

Acknowledgement

Thank you for Xavier Duval’s French proof reading.

References

[1] Furlan N, Waldron M, Shorter K, Gabbett TJ, Mitchell J, Fitzgerald E, et al. Running-intensity fluctuations in elite rugby sevens performance. Int J Sports Physiol Perform 2015;10,802–7.

[2] Suarez-Arrones L, Núñez J, Sáez de Villareal E, Gálvez J, Suarez-Sanchez G, Munguía-Izquierdo D. Repeated-high-intensity-running activity and internal training load of elite rugby sevens players during international matches: a comparison between halves. Int J Sports Physiol Perform 2016;11,495–9.

[3] Higham DG, Pyne DB, Anson JM, Eddy A. Movement patterns in rugby sevens: effects of tournament level, fatigue and substitute players. J Sci Med Sport 2012;15,277–82.

[4] Granatelli G, Gabbett TJ, Briotti G, Padulo J, Buglione A, D'Ottavio S, et al. Match analysis and temporal patterns of fatigue in rugby sevens. J Strength Cond Res 2014;28,728–34.

[5] Ross A, Gill ND, Cronin JB. A comparison of the match demands of international and provincial rugby sevens. Int J Sports Physiol Perform 2015;10,786–90.

[6] Vieira A, Siqueira AF, Ferreira-Junior JB, do Carmo J, Durigan JQ, Blazevich A, et al. The effect of water temperature during cold-water immersion on recovery from exercise-induced muscle damage. Int J Sports Med 2016;37,937–43.

[7] Pointon M, Duffield R. Cold water immersion recovery after simulated collision sport exercise. Med Sci Sports Exerc 2012;44,206–16.

[8] Pointon M, Duffield R, Cannon J, Marino FE. Cold-water immersion recovery following intermittent-sprint exercise in the heat. Eur J Appl Physiol 2012;112,2483–94.

[9] Bottinelli R, Canepari M, Pellegrino MA, Reggiani C. Force-velocity properties of human skeletal muscle fibres: myosin heavy chain isoform and temperature dependence. J Physio 1996;495,573–86.

[10] Bigland-Ritchie B, Thomas CK, Rice CL, Howarth JV, Woods JJ. Muscle temperature, contractile speed, and motoneuron firing rates during human voluntary contractions. J Appl Physiol 1992;73:2457–61.

[11] Chesterton L, Foster N, Ross L. Skin temperature response to cryotherapy. Arch Phys Med Rehabil 2002;83,543–9.

[12] Drinkwater EJ, Behm DG. Effects of 22 °C muscle temperature on voluntary and evoked muscle properties during and after high-intensity exercise. Appl Physiol Nutr Metab 2007;32,1043–51.

[13] Robertson V, Ward A, Low J, Reed A. Electrotherapy explained principles and practice (4th ed.). Edinburgh: Elsevier Butterworth-Heinemann; 2006.

[14] Wilcock IM, Cronin JB, Hing WA. Physiological response to water immersion: A method for sport recovery. Sports Med 2006;36,747–65.

[15] Swain DP, Abernathy KS, Smith CS, Lee SJ, Bunn SA. Target heart rates for the development of cardiorespiratory fitness. Med Sci Sports Exerc 1994;26,112–6.

[16] Computer Sports Medicine, Inc. HUMAX®/NORM™ testing & rehabilitation system: User's guide model 770. Stoughton, MA: Computer Sports Medicine, Inc; 2005.

[17] Impellizzeri FM, Bizzini M, Rampinini E, Cereda F, Maffiuletti NA. Reliability of isokinetic strength imbalance ratios measured using the Cybex NORM dynamometer. Clin Physiol Funct Imaging 2008;28,113–9.

[18] Carlock J, Smith S, Hartman M, Morris R, Ciroslan D, Pierce K, et al. The relationship between vertical jump power estimates and weightlifting ability: a field-test approach. J Strength Cond Res 2004;18,534–9.

[19] Beekhuizen K, Davis M, Kolber M, Cheng M. Test-retest reliability and minimal detectable change of the hexagon agility test. J Strength Cond Res 2009;23:2167–71.

[20] 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;46,233−40.

[21] Brown LE. Isokinetics in human performance. Champaign, Ill.: Human Kinetics; 2000.

[22] Hernández-Davó JL, Sabido R. Rate of force development: reliability, improvements and influence on performance. A review. Eur J Hum Mov 2014;33,46–69.

[23] Yanagisawa O, Otsuka S, Fukubayashi T. Effect of cooling during inter-exercise periods on subsequent intramuscular water movement and muscle performance. Scand J Med Sci Sports 2014;24,11–7.

[24] Bračič M, Hadžič V, Čoh M, Dervišević E. Relationship between time to peak torque of hamstrings and sprint running performance. Isokinet Exerc Sci 2011;19,281–6.

[25] Oksa J, Ducharme M, Rintamaki H. Combined effect of repetitive work and cold on muscle function and fatigue. J Appl Physiol 2002;92,354–61.

[26] Cornwall M. Effect of temperature on muscle force and rate of muscle force production in men and women. J Orthop Sports Phys Ther 1994;20,74–80.

[27] Peiffer JJ, Abbiss CR, Nosaka K, Peake JM, Laursen PB. Effect of cold water immersion after exercise in the heat on muscle function, body temperatures, and vessel diameter. J Sci Med Sport 2009;12,91–6.

[28] Dewhurst S, Riches PE, De Vito G. Moderate alterations in lower limbs muscle temperature do not affect postural stability during quiet standing in both young and older women. J Electromyogr Kinesiol 2007;17,292–8.

[29] Yona M. Effects of cold stimulation of human skin on motor unit activity. Jpn J Physiol 1997;47,341–8.

[30] Kannus P. Isokinetic evaluation of muscular performance: implications for muscle testing and rehabilitation. Int J Sports Med 1994;15,s11–8.

[31] Maffiuletti N, Aagaard P, Blazevich A, Folland J, Tillin N, Duchateau J, et al. Rate of force development: physiological and methodological considerations. Eur J Appl Physiol 2016;116,1091–116.

[32] Cronin JB, Hansen KT. Strength and power predictors of sports speed. J Strength Cond Res 2005;19,349–57.

[33] Markström JL, Olsson C. Countermovement jump peak force relative to body weight and jump height as predictors for sprint running performances: (in)homogeneity of track and field athletes? J Strength Cond Res 2013;27,944–53.

[34] Nuzzo J, McBride J, Cormie P, McCaulley G. Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. J Strength Cond Res 2008;22,699–707.

[35] Buckthorpe M, Morris J, Folland JP. Validity of vertical jump measurement devices. J Sports Sci 2012;30,63–9.

[36] White GE, Rhind SG, Wells GD. The effect of various cold-water immersion protocols on exercise-induced inflammatory response and functional recovery from high-intensity sprint exercise. Eur J Appl Physiol 2014;114,2353–67.

[37] Byrne C, Twist C, Eston R. Neuromuscular function after exercise-induced muscle damage: theoretical and applied implications. Sports Med 2004;34,49–69.

[38] Patterson SM, Udermann BE, Doberstein ST, Reineke DM. The effects of cold whirlpool on power, speed, agility, and range of motion. J Sports Sci Med 2008;7,387–94.

[39] Young WB, Dawson B, Henry, GJ. Agility and change-of-direction speed are independent skills: implications for training for agility in invasion sports. Int J Sports Sci Coach 2015;10,159–69.

Table 1 Demographic characteristic of participants.

Characteristics	IWI group (n = 13)	RWI group (n = 18)	Control group (n = 22)	*P* value
Age (y)	22.9 ± 2.4	21.8 ± 3.4	20.7 ± 2.4	0.074
Sex (no. and %)				0.995
Male	7 (53.8%)	10 (55.6%)	12 (54.5%)	
Female	6 (46.2%)	8 (44.4%)	10 (45.5%)	
Body height (m)	1.685 ± .104	1.682 ± .097	1.685 ± .089	0.993
Body weight (kg)	64.1 ± 10.2	64.6 ± 12.3	62.4 ± 13.7	0.836
Body–mass index (kg/m^2)	22.5 ± 1.3	22.7 ± 3.4	21.7 ± 3.1	0.565
Percentage of body fat (%)	14.2 ± 6.6	14.8 ± 7.0	14.8 ± 7.3	0.960
Resting heart rate (beats/min)	68.2 ± 7.1	70.1 ± 7.4	66.0 ± 8.3	0.258
Resting blood pressure				
Systolic blood pressure (mmHg)	113.4 ± 6.9	112.8 ± 11.8	117.9 ± 9.3	0.214
Diastolic blood pressure (mmHg)	70.9 ± 5.9	70.4 ± 8.5	71.6 ± 9.0	0.898
Physical-activity level (MET · h/wk)	133.4 ± 108.8	142.8 ± 74.9	147.0 ± 113.9	0.929
Rugby experience (y)	3.2 ± 1.3	3.3 ± 2.5	4.9 ± 4.0	0.155
Training volume (h/wk)	7.8 ± 2.9	6.5 ± 4.0	6.9 ± 2.9	0.577

Injury history				
Mild concussion (no. and %)	2 (15.4%)	0 (0%)	2 (9.1%)	0.261
Sprained ankle (no. and %)	10 (76.9%)	14 (77.8%)	16 (72.7%)	0.925
Sprained knee (no. and %)	2 (15.4%)	5 (27.8%)	3 (13.6%)	0.489

Notes: Means ± standard deviations are presented unless otherwise specified.

IWI: ice water immersion; RWI: room temperature water immersion

Table 2 Outcome measures.

Outcome measures	IWI group (n = 13)		RWI group (n = 18)		Control group (n = 22)		Group effect	Time effect	Group × time effect
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	*P* value	*P* value	*P* value
Body weight-adjusted isokinetic peak torque (Nm/kg) at 60°/s									
Knee extensors	290.00 ± 35.38	265.38 ± 37.65†	277.61 ± 36.99	264.72 ± 47.17	269.05 ± 60.93	265.87 ± 58.41	0.826	0.001*	0.108
Knee flexors	177.69 ± 38.71	171.31 ± 39.63	160.83 ± 27.02	164.50 ± 25.11	155.44 ± 30.05	159.40 ± 26.77	0.243	0.892	0.337
Time to peak torque (s) at 60°/s									
Knee extensors	0.64 ± 0.12	0.62 ± 0.11	0.68 ± 0.14	0.62 ± 0.12†	0.72 ± 0.13	0.70 ± 0.13	0.148	0.031*	0.493
Knee flexors	0.46 ± 0.10	0.44 ± 0.10	0.57 ± 0.14	0.42 ± 0.08†	0.50 ± 0.14	0.47 ± 0.15	0.525	< 0.001*	< 0.001*
CMJ height (cm)	39.41 ± 9.49	37.83 ± 8.45†	36.68 ± 8.49	35.83 ± 7.56	37.16 ± 8.61	37.11 ± 8.71	0.746	0.002*	0.064
Hexagon agility test time (s)	12.17 ± 2.67	11.01 ± 2.31†	12.51 ± 2.16	11.37 ± 1.35†	11.28 ± 1.36	10.79 ± 1.39†	0.263	< 0.001*	0.168

Notes: Means ± standard deviations are presented unless specified otherwise; IWI: ice water immersion; RWI: room temperature water immersion

* Denotes a difference significant at $P < 0.05$.

† Denotes a difference significant at $P < 0.05$ compared with the baseline value.

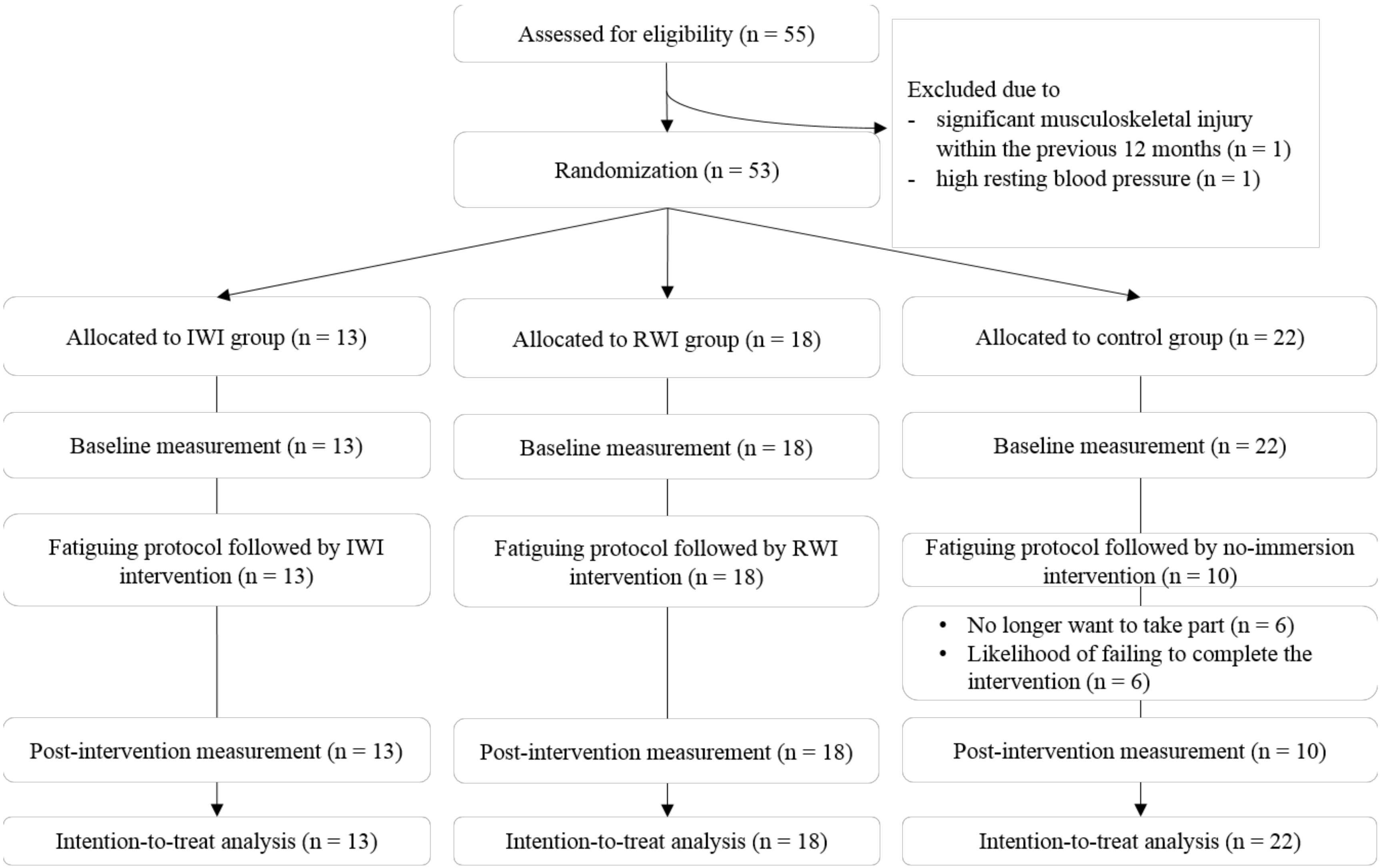

Figure 1 Study flow chart.

Notes: IWI**:** ice water immersion; RWI: room temperature water immersion