SPORTS MEDICINE AND BIOMECHANICS

Short-term effects of two different recovery strategies on muscle contractile properties in healthy active men: A randomised cross-over study

Esther Mur-Gimeno (a, b), Raquel Sebio-Garcia (b, c), Joan Solé (d), Agustín Lleida (e) and Gerard Moras (d)

[a]School of Health Sciences TecnoCampus, University Pompeu Fabra, Mataró, Spain; [b]Research Group in Attention to Chronicity and Innovation in Health (GRACIS), University Pompeu Fabra, Mataró, Spain; [c]Department of Rehabilitation, Hospital Clínic, de Barcelona, Barcelona, Spain; [d]High Performance Department, National Institute of Physical Education. Barcelona, Spain; [e]Team Technical Staff, Liga Deportiva Alajuelense, Alajuela, Costa Rica

ABSTRACT

The aim of this study was to compare the immediate effects of cold-water immersion (CWI) and hot-water immersion (HWI) versus passive resting after a fatigue-induced bout of exercise on the muscle contractile properties of the Vastus Medialis (VM). We conducted a randomised cross-over study involving 28 healthy active men where muscle contractile properties of the VM wer recorded using Tensiomyography (TMG) before and after CWI, HWI or passive resting and up to one-hour post-application. The main outcomes obtained were muscle displacement and velocity of deformation according to limb size (Dmr and Vdr). Our results showed a significant effect of time ($F(3.9,405) = 32.439$; $p < 0.001$; $\eta_{2p} = 0.29$) and the interaction between time and temperature ($F(7.9,405) = 5.814$; $p < 0.001$; $\eta_{2p} = 0.13$) on Dmr but no for temperature

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Introduction

Fastening recovery after exercise has been one hot topic in the field of sports medicine for several decades, with a wide variety of techniques and strategies scrutinised over the years in the pursue of the best possible method. The use of hydrotherapy as a recovery strategy is widely implemented given its well- established physiological benefits on several body systems (Halson et al., 2008; Wilcock et al., 2006). Cryotherapy in the form of cold-water immersion (CWI), has been traditionally applied as the optimal strategy to enhance muscle recovery after exercise given its effects on pain, swelling and inflammation (Hohenauer et al., 2015). However, despite these well- known physiological effects, inconsistent results are found across studies, which may be due to the lack of consensus regarding water temperature and immersion times (Machado et al., 2016). Furthermore, recent investigations have demonstrated that cold-water immersion may actually be acutely detrimental to muscle performance as it impairs glycogen repletion and resynthesis (Cheng et al., 2017). On the other hand, hot-water immersion (HWI) has received comparatively much less attention both in research and sports field practice and its application to enhance muscle recovery is yet to be determined. Nevertheless, some studies have shown that HWI can improve perception of fatigue and increase loading tolerance in some environments (Dn et al., 2020). In addition, contrast therapy (combining CWI and HWI) has also been shown to effectively reduce delayed onset muscle soreness and faster acute recovery after exercise (P et al., 2011; Versey et al., 2013).

Muscle contractile properties such as velocity and magnitude of contraction or time to respond are a key determinant of sports performance (Fitts et al., 1991). In recent years, tensiomyography (TMG) has emerged as a valid (Lohr et al., 2019) and highly reliable technique (Martín-Rodríguez et al., 2017) to assess these muscle contractile properties by recording muscle radial displacement in response to a single electrical stimulus (Valencic & Knez, 1997). Although TMG does not measure muscle strength directly, it has shown good correlation with the estimated one maximum repetition (1RM) and the maximal voluntary isometric contraction (De Paula Simola et al., 2015) as well as with muscle tone (Valencic & Knez, 1997), muscle composition (Dahmane et al., 2005), power (Valenzuela et al., 2018) and muscle fatigue (Pereira et al., 2020; R et al., 2016). As such, the use of TMG in sports medicine is increasing, especially to assess neuromuscular properties of different muscles (Alvarez-Diaz et al., 2016) but also functional performance (Pereira et al., 2020) and exercise recovery (García-Sillero et al., 2021). In a previous study, we observed that water immersion at either hot or cold temperature elicited opposite behaviours in muscle contractile properties assessed with TMG (Gimeno et al., 2020). However, no studies so far have assessed whether these changes observed in muscle contractile properties might impact muscle recovery. Therefore, the aim of this study was 1) to compare the effects of two different recovery strategies (HWI and CWI) versus passive rest across time after a fatigue-induced exercise on the Vastus Medialis (VM) contractile properties using TMG. Based on previous studies (Gimeno et al., 2020), we hypothesised that immersion in HWI would result in a decrease of muscle stiffness comparing to CWI and passive rest suggesting a faster muscle recovery after HWI.

CONTACT Raquel Sebio-Garcia

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Methods

Design

We conducted a randomised cross-over study with repeated measures over a period of 2 months (January and February). The study protocol was conducted following the Declaration of Helsinki recommendations and was approved by the local ethics committee. All subjects were properly informed about the study purpose and written consent was obtained before any formal testing.

Subjects

Participants were recruited from a Laboratory for High Athlete Performance and 45 healthy active subjects were initially screened for inclusion. Participants were excluded if 1) they reported any significant neuromuscular or musculoskeletal injury in the assessed limb over the previous six months (such as fibrillary rupture, ligament sprain, fracture, dislocation or meniscus injury) and b) extenuating exercise or consumption of stimulants in the 48 hours previous to any of the assessments. After screening, 15 subjects were deemed not eligible (three have had a ligament sprain, one a fracture and 11 refused participation) and two were lost during the study period, therefore 28 healthy active men (mean age 28 ± 5 years, BMI 23.2 ± 1.12, minimum leg perimeter 47.9 ± 3 cm, maximum leg perimeter 62.9 ± 2.5 cm and anteroposterior diameter of the VM 47.8 ± 4 cm) participated in the study.

The sample size was calculated based on previous investigations in our research group (Gimeno et al., 2020) were we found a mean difference of 1 mm difference in maximal radial displacement between water temperatures, with a standard deviation of 1.65 mm, using a statistical power of 0.80 and 95% confidence interval, we needed at least 24 participants for this study.

Procedures

Participants were evaluated on four non-consecutive days. On the first day, anthropometric measurements of body weight, height and lower limb perimeter (minimum and maximum) were taken. In addition, the anteroposterior diameter of the VM was obtained by ultrasound imaging. Participants were then asked to perform an eight-repetition maximum test (8RM) for the knee extension using a quadriceps bench which would later be used for the fatigue-induced exercise. To calculate the 8RM, we first measured each subject's 1RM according to the international protocols (Brown & Weir, 2001). Then, participants performed 5–10 repetitions at 50% of 1RM followed by a 1-minute rest. Next, load was increased to 80% 1RM for three to five repetitions more. After another 1-minute break, weight was progressively increased until the 8RM was achieved (muscle failure). During the test, participants had to perform the exercise following a pre-established pace of 60 Hz measured with a metronome (Moras et al., 2009).

On the second, third and fourth day, participants were measured using TMG before and after a fatigue-induced protocol that consisted of five sets of eight repetitions at each individual's 8RM with a 3-minute break between sets. The repetitions were performed according to the pre-established pace of 60 Hz. Immediately after, subjects were randomly allocated to one of the three recovery strategies for 15 minutes as recommended by the literature (Machado et al., 2016): a) hot- water immersion at 42º; b) cold-water immersion at 10º or c) passive resting on a bench. A one-week wash-out period was allowed between each recovery strategy. Water immersion was performed with participants seated in a Jamaica massage bathtub of 250 L capacity and water level slightly over the hips as described in a previous study (Pereira et al., 2020). Water temperature was monitored continuously to maintain a 10 ± 1°C and 42º±2°C during cold- and hot-water immersion respectively with ambient temperature at 22 ± 1°C. Core temperature was monitored using a thermometer during and after immersion.

TMG recordings

The protocol used for the TMG assessment has been described in the literature (Gimeno et al., 2020; Piqueras- Sanchiz et al., 2020). Measurements were performed by one of the study authors (EM) who was previously trained for by an expert in the field (GM) for several weeks. TMG parameters were obtained on the dominant leg with the subject lying facing up and the assessed limb positioned placed on a foam cushion with the knee bent at 30º (Figure 1). A digital displacement transducer (GK 40, Panoptik d.o.o., Ljubljana, Slovenia), which incorporates a spring of 0.17 N mm^{-1} providing an initial pressure of 1.5×10^{-2} N/ mm^2 was set perpendicular to the muscle belly to obtain VM radial displacement (Dahmane et al., 2005). Sensor location was determined anatomically and marked with a dermatological pen (Delagi et al., 2005). Two square- shaped (4.5 x 4.5 cm) 2 mm-thick self-adhesive electrodes (RM 4545 Rehab Medick, Spain) were placed symmetrically distal and proximal to the sensor tip (3 cm each way) and a TMG-S1 stimulator (EMF-Furlan I Co. d.o.o., Ljubljana, Slovenia) was used. Electrical stimulation was provided by means of a square pulse of 1 ms and intensity was initially set at 50 mA and increased 10 mA every 10–15 seconds until no further change in Dm was observed or maximal stimulator output was achieved (110 mA) (Tous-Fajardo et al., 2010). Baseline parameters were obtained after two consecutive measurement protocols separated by five minutes and mean values were used for analysis.

Outcomes

TMG parameters were obtained as at baseline (PRE), immediately after the fatigue-induced protocol (POST-Fatigue), right after the exercise recovery strategy (POST-Recovery) and every 15 minutes up to one hour (POST15′, POST30′, POST45′ and POST60′). The following parameters were obtained from the displacement-time graph: a) maximal displacement (Dm) in millimiters and b) contraction time (Tc), as the time from 10% to 90% of the maximal displacement curve. According to the literature, both Dm and Tc are the easiest parameters to reproduce (intra-class correlation coefficient 0.82–0.99 and 0.70–0.99 respectively) and the more reliable (Martín-Rodríguez et al., 2017; Tous- Fajardo et al., 2010). From these two main parameters (Dm and Tc) we derived a third one (velocity of deformation or Vd) using the equation $Vd = Dm/Tc$ which represents the rate of contraction observed between 10% and 90% of Dm ($\Delta DM/dt$) (García-Manso et al., 2011; Macgregor et al., 2018; Tous-Fajardo et al., 2010). Contrary to Tc, Vd is not dependent on Dm (Macgregor et al., 2018). We used the term velocity of deformation instead of the most common velocity of contraction because it reflects the rate of change in the muscle belly displacement per time and to avoid confusion with the velocity of contraction of the muscle sarcomeres (Valenzuela et al., 2018). In addition, to avoid bias derived by body composition, both Dm and Vd were relativized for each individual according to the anteroposterior diameter of the vastus medialis measured by ultrasound imaging (Dmr and Vdr).

Statistical analysis

A descriptive analysis of the main categorical and continuous variables was performed initially prior to further analysis. Continuous variables are expressed in mean and standard deviation (SD) while categorical variables are represented in absolute values and corresponding percentage. Distribution was assessed for every continuous variable using the Shapiro–Wilk test. Variables not normally distributed were transformed before analysis. First, a one-way ANOVA was conducted to assess differences between groups on Dmr, Tc and Vdr at each given time. A two-way ANOVA with repeated measures was then performed to assess the effects of the condition (HWI, CWI or passive rest) as the between-subject factor and time (PRE, POST-Fatigue, POST-Recovery, POST15′, POST30′, POST45′ and POST60′) as the within-subject factor, as well as the interaction of both. When sphericity was violated, the Greenhouse– Geisser correction was used. Homogeneity of the variance was checked using Levene's Test. When a significant F ratio was obtained, a Bonferroni post-hoc test was used to evaluate time and temperature differences. Partial eta-squared effects sizes were also calculated to account for the effect of time and temperature on Tc, Dmr and Vdr. Statistical analysis was performed using the statistical software SPSS v.21, IBM® (IBM Corporation, Chicago Illinois, USA) and P values < 0.01 were considered statistically significant according to Bonferroni correction for multiple comparisons.

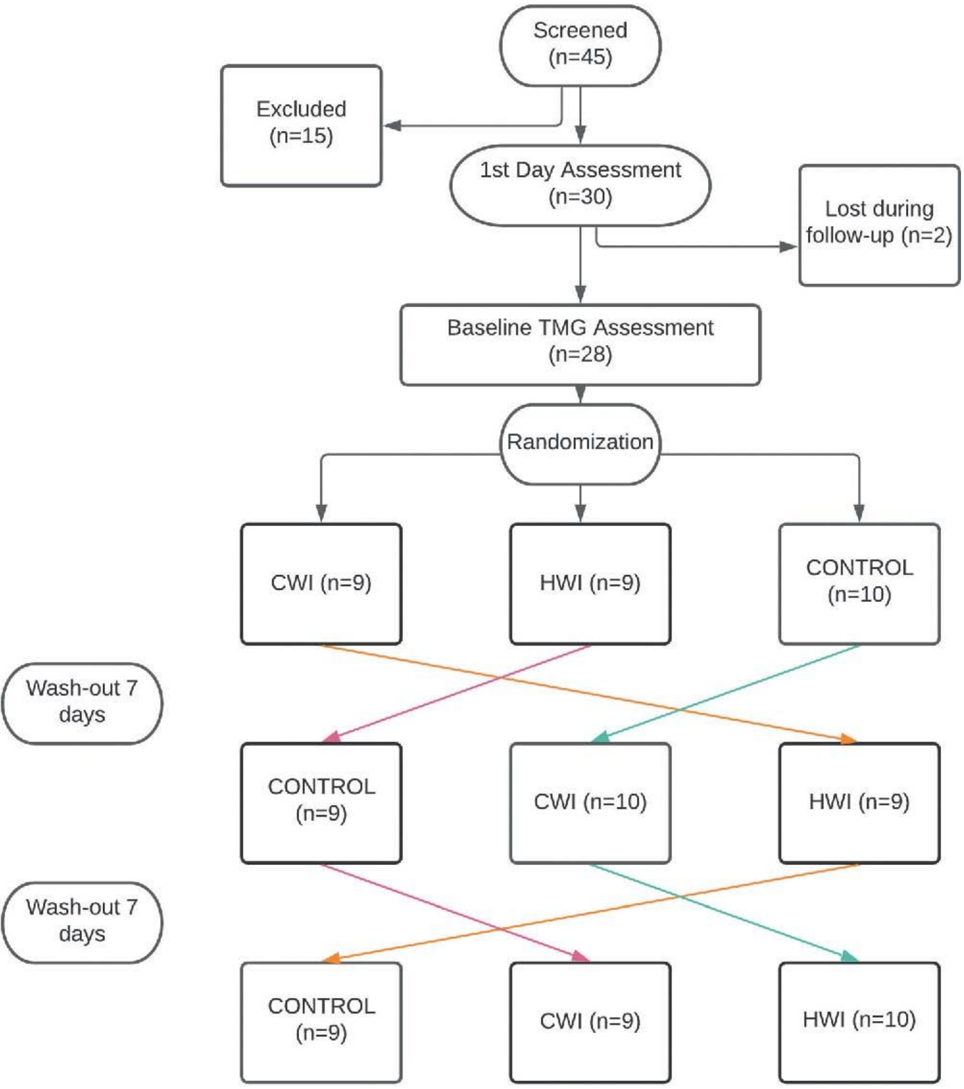


Figure 1.

Flow diagram for the study participants and randomisation order.

Results

We found a significant effect for time on Dmr as well as the interaction between time and condition but not for condition alone (Table 1). Pairwise comparison showed that significant differences were found between HWI and CWI right after application (mean difference +4.02 ± 1.07 mm; 95% CI: 0.75–7.3; p = 0.001) (Figure 2). We also observed a tendency at 15 minutes favouring HWI (mean difference +3.08 ± 1.06 mm; 95% CI: −0.14, +6.3; p = 0.015). With regard to Vdr, a significant effect was found for both time and condition as well as the interaction between both factors ($p < 0.001$) (Table 1). Pairwise comparisons showed significant differences between HWI and CWI post-immersion (mean difference +0.29 ± 0.06s; 95% CI: 0.11– 0.46; $p < 0.0001$), 15′ and 45′ post-application (mean difference +0.2 ± 0.05s, 95% CI: 0.03–0.37; p = 0.001 and +0.2 ± 0.06s; 95% CI: 0.02–0.38; p = 0.004 respectively) (Figure 3). Comparing to passive resting, we found differences with HWI immediately after and at 45 minutes (−0.16 ± 0.06s; p = 0.015 and mean difference −0.19 ± 0.06s; p = 0.008 respectively) and with CWI at 15 minutes (+0.18 ± 0.05s., p = 0.005). Finally, we also found a significant effect of time (F (4.8, 486 = 3.30, p = 0.007; η_{2p}= .039) and the interaction between condition x time (F (9.7,486) = 2.45, p = 0.008; η_{2p}= .057) on Tc but not for condition alone (F(Halson et al., 2008, p. 81) = 2.52, p = 0.087; η_{2p}= .06).

Discussion

The aim of this study was to compare the effects of two different recovery strategies versus passive resting on the muscle contractile properties of the vastus medialis. Our findings show that there is a significant interaction between recovery strategy and time for both Dm and Vd when they are relativised according to limb size (Dmr and Vdr). Specifically, we observed a greater increase in Dmr after HWI comparing to CWI immediately after and during the first 15 minutes post-immersion. Furthermore, Vdr was also shown to be higher after HWI than CWI immediately after immersion as well as 15 and 45′ minutes later, overall pointing out to a faster muscle after recovery with HWI than with CWI.

Muscle contractile properties (De Paula Simona et al., 2015) are highly important for muscle performance, as modifications in these properties are expected to influence power, strength and resistance to fatigue. TMG is one of the mechanomyography techniques that record several muscle contractile properties (muscle belly displacement, contraction time, sustain time, delay time) evoked through transcutaneous neuromuscular stimulations. In addition, the velocity of deformation (Vd) can be calculated using different variations of the same parameters (Dm and Tc) with the most appropriate method yet to be defined (Macgregor et al., 2018). Vd can be used as an indirect measure of muscle performance in terms of speed and power (Loturco et al., 2016; Valenzuela et al., 2018), with higher values suggesting a more responding, rapid muscle while a reduction in this parameter is regarded as an indirect measure of muscle fatigue (García-manso et al., 2011; Pereira et al., 2020; R et al., 2016). In this study, a significant effect was found for water temperature and time on Vdr, showing a higher increase after HWI than CWI or passive resting. While little is known about the effects of HWI on muscle performance and exercise recovery, the use of CWI has been largely investigated, although results are controversial (Broatch et al., 2014; Kwiecien et al., 2021; Machado et al., 2017; Roberts et al., 2014). As reported in the study by Cheng et al. (Cheng et al., 2017) cryotherapy might actually attenuate recovery rates by reducing the ability of the muscle to restore glycogen levels. Comparing to cooling, they observed that heating accelerated recovery from fatigue. In a study conducted by Broatch et al. (Broatch et al., 2014) comparing CWI with thermoneutral placebo water immersion, CWI actually resulted in a decrease in muscle strength, readiness for exercise, pain and vigour. These results caused the authors to hypothesise that the physiological effects of CWI are at least in part, placebo-related. In a similar design to our study, Jakeman et al. explored the effects of a single bout of CWI for 10 minutes immediately following damage-inducing exercise and failed to find any significant effect of the group allocation or the interaction between group and time on any of the variables assessed (Jakeman et al., 2009). Garcia et al. also compared immersion for 20 minutes in cold water at 9°C with passive resting on a bench and reported a decrease in the agility T-test and the countermovement jump test immediately after CWI (Garcia et al., 2016). When these tests were performed 12-hours later, no differences were found. According to the study published by Petrofsky et al., both CWI and HWI are effective in reducing muscle damage after exercise but application of heat during the first two hours post-exercise was superior to cold for the recovery of muscle strength on the second day after exercise (Petrofsky et al., 2015). However, when heat and cold were applied 24 hours later, the cold group appeared to recover their strength faster than the heat group. Based on the results of these studies, it seems that the application of CWI could be acutely detrimental for muscle performance but enhance recovery on the medium-long term by means of reducing pain, decrease core temperature, reduce cardiovascular strain and assist removal of muscle wasting (Ihsan et al., 2016; Petrofsky et al., 2015).

As a greater radial displacement is usually found in more relaxed or hypotonic muscles, Dm assessed with TMG is regarded as an indirect measure of muscle stiffness (Evetovich et al., 1997; Valencic & Djodjevic, 2001). Although we did not find a significant effect of treatment on this parameter, there was a significant difference immediately after application as a well as a tendency at 15 minutes, suggesting that HWI can rapidly decrease muscle stiffness after a muscle-damaging exercise protocol. This assumption is in line with recent studies and challenge the well-established conception that cold-water therapy is an optimal recovery strategy during sports performance. For instance, Point et al., in a study published in 2018, concluded that the application of 4 sets of 4′ of air-pulsed cryotherapy resulted in an increase in muscle stiffness after

Table 1. Two-way ANOVA for the comparison of Dmr, Vdr and Tc changes over time according to the recovery strategy.PRE	POST-Fatigue	POST-Recovery	POST15′	POST30′	POST45′	POST60′				
Mean ± SD (95% CI)	Time effect	Temperature effect	Temperature x tim							
Dmr	**CWI**	16.9 ± 3.6 (15.5–18.3)	15.1 ± 3.8 (13.6–16.6)	14.1 ± 2.7 (13–15.1)	14 ± 3 (12.9–15.2)	15.8 ± 3.6 (14.1–17.2)	17.4 ± 3.6 (16–18.8)	17.2 ± 3.7 15.8–18.7)	F(3.9, 405) = 32.439; p < 0.001; η_{2p} = 0.29	F 2 (r
HWI	18.9 ± 3.9 (17.4–20.4)	15.8 ± 4.3 (14.1–17.4)	**18.1 ± 5.1 (16.1–20)***	17.1 ± 4.6 (15.3– 18.9)	16.9 ± 5 (14.9– 18.8)	19.5 ± 4.5 (17.7– 2				
CON	17.5 ± 3.9 (16– 19)	14.9 ± 4 (13.4– 16.5)	15.7 ± 3.9 (14.2– 17.3)	16.5 ± 4.1 (14.9– 18.1)	16.5 ± 4.9 (14.6–18.4)	17.1 ± 4.9 (15.2– 1				
Vdr	**CWI**	0.87 ± 0.19 (0.8–0.98)	0.8 ± 0.24 (0.7–0.86)	0.65 ± 0.15 (0.6– 0.71)	**0.65 ± 0.17 (0.6–0.72)¥**	0.73 ± 0.23 (0.64–0.82)	0.81 ± 0.2 (0.73– 0.9)	0.86 ± 0.23 (0.77–0.95)	F(5.2, 486) = 23.068; p < 0.001 η_{2p} = 0.22	F 4 ((
HWI	0.97 ± 0.22 (0.88–1.1)	0.8 ± 0.24 (0.71–0.9)	**0.94 ± 0.27 (0.84–1.05)***	**0.86 ± 0.23 (0.77–0.95)***	0.86 ± 0.23 (0.78–0.95)	**1.01 ± 0.22 (0.92–1.1)†***				
CON	0.89 ± 0.22 (0.81–0.98)	0.76 ± 0.18 (0.69–0.83)	0.78 ± 0.2 (0.7– 0.86)	0.83 ± 0.2 (0.75– 0.92)	0.82 ± 0.22 (0.74–0.9)	0.82 ± 0.24 (0.73–0				

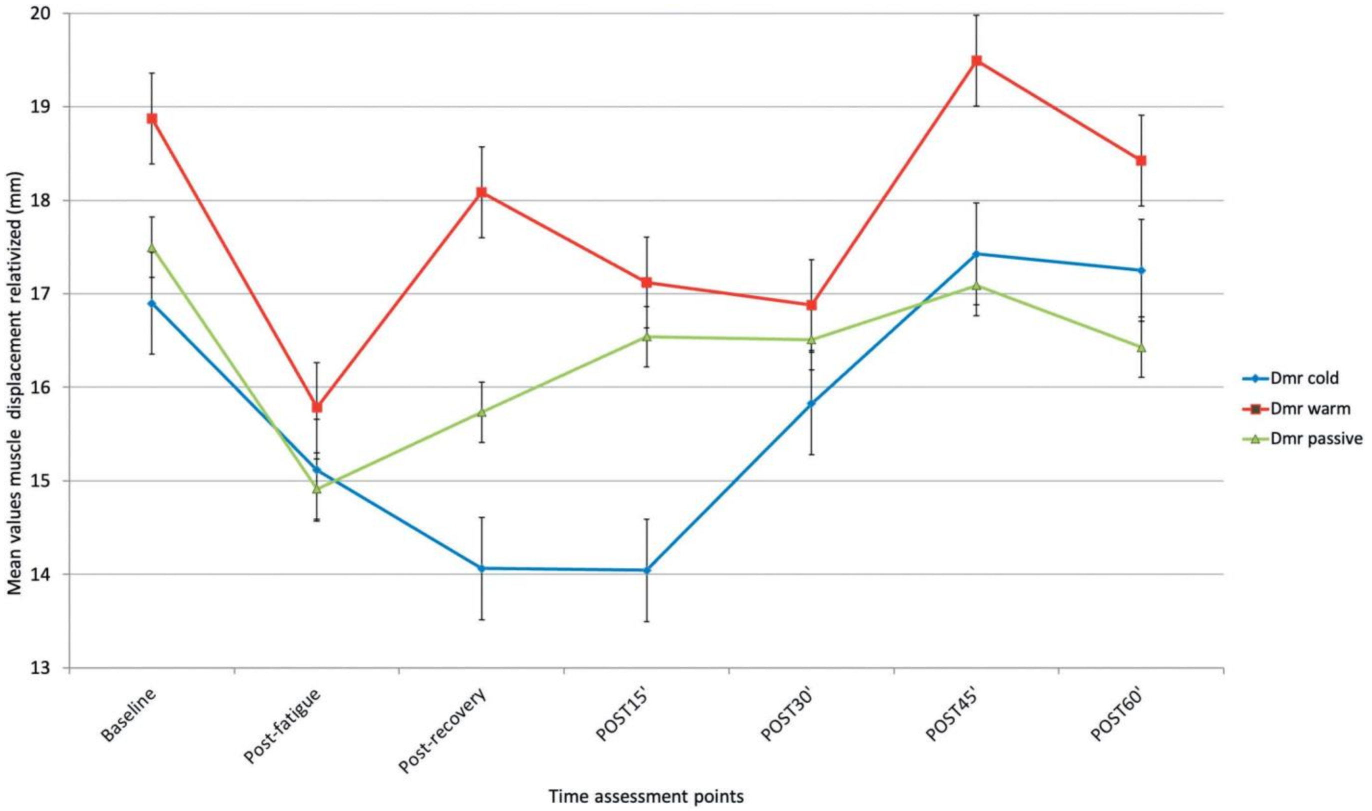
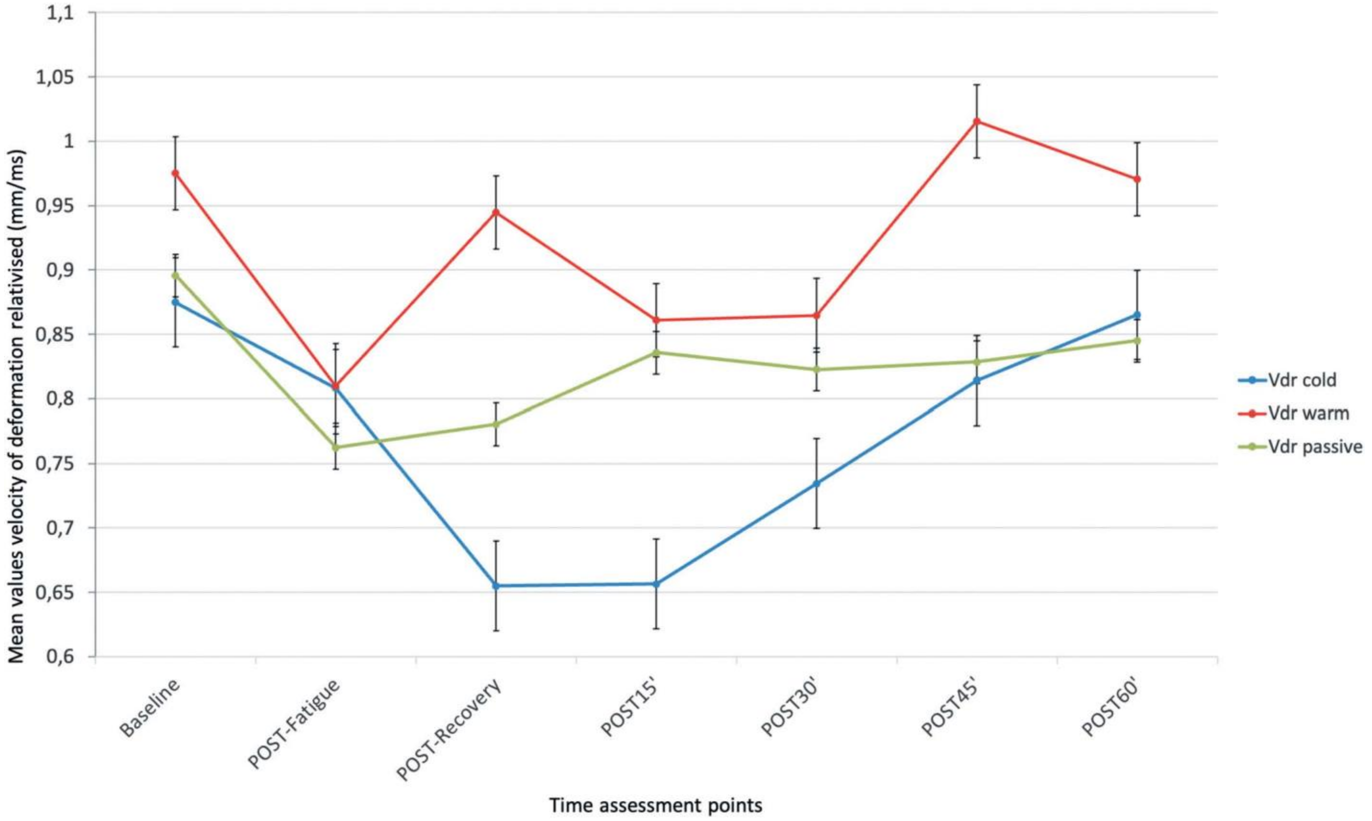


Figure 2.
Changes in muscle displacement relativized (Dmr) according to the antero-posterior axis. Bars represent standard error of the mean.

Figure 3.
Changes in velocity of deformation relativized (Vdr) according to the antero-posterior axis. Bars represent standard errors of the mean.



the second pulse which peaked 30′ after the last application (Point et al., 2018). This increase in stiffness was mirrored by a decrease in intra-muscular temperature. In another study by Cheng et al. (Cheng et al., 2017), including both experiments in humans and in mice, the authors examined the differences in exercise performance during an all-out arm-cycling endurance exercise after the application of cold- or hot-water. After two hours of recovery with either hot or cold applications, they observed that muscle performance was better preserved in the heat group comparing to the cold group which they attributed to an impairment in glycogen resynthesis observed after cooling. In both studies, the highest difference was observed at 30 minutes post-recovery, while in our study, no differences were seen between water temperatures beyond that duration. It is possible that type of cryotherapy as well as temperature and duration used in both protocols are responsible for this event. Interestingly, HWI was no better than passive rest to increase Dmr after a fatigue-induced exercise protocol which relates more to a detrimental effect of CWI on muscle stiffness than a positive effect of HWI.

There are several potential mechanisms by which water immersion might modify muscle contractile properties related to the physiological of buoyancy, hydrostatic pressure, density and temperature (Torres-Ronda & Schelling I Del Alcázar, 2014). Although it is impossible to isolate the effects each feature in particular, research has shown that water temperature and duration of immersion are most likely the main factors accounting for the effects on exercise recovery. Hydrostatic pressure causes a blood flow shift towards the thoracic region which can help with the recovery process by assisting metabolic clearance. The magnitude of this effect is affected by body position and depth of immersion, with increase effects when more body volume being immersed (Wilcock et al., 2006). However, in a study comparing standing with seated immersion versus control, no differences were found in exercise recovery after a high-intensity interval training (Leeder et al., 2015), suggesting that hydrostatic pressure by itself had little effect on muscle recovery. Water temperature during immersion is known to affect both core temperature and muscle temperature. In the study by Myer et al., a mean decrease of 7°C was observed after a 20-minute CWI at 10°C. In a subsequent study by Rupp et al. time to decrease muscle temperature 8°C with CWI was 39 minutes (Rupp et al., 2012). Furthermore, in the study by Point et al., the decrease in muscle temperature was correlated to a direct increase in muscle stiffness. These findings suggest that the decrease in muscle temperature with CWI could be the main responsible for the decrease in Dmr and Vdr observed in our study. Nevertheless, studies assessing changes in muscle temperature with maximal strength or power performance, show conflictive results (Stanley et al., 1994). Given that little differences were observed between HWI and passive resting, it seems that the decrease in muscle temperature caused by CWI was probably one of the most influencing factors accounting for the differences observed between the two recovery strategies. Unfortunately, we did not measure intra-muscular temperature to establish whether these changes in muscle contractile properties were directly correlated with changes in muscle temperature. Nevertheless, considering the inconsistent results reported in the literature between muscle temperature and muscle performance we cannot rule out other important mechanisms behind the differences observed between HWI and CWI. In addition, large variations are found in terms of water immersion protocols (temperature of immersion, duration, etc.) which are also known to influence the physiological responses obtained (Machado et al., 2016).

This study has some limitations that must be discussed. First of all, subjects of this investigation were only men, thus results should not be extrapolated into a female population which may show a different pattern/behaviour. Although the main parameters (Dm and Vd) were relativised to the anteroposterior diameter of the quadriceps, differences in tissue morphology and muscle fibre composition as a result of different training modalities were not taken into account and could have influenced the results. In addition, we did not record intra-muscular temperature as this is an invasive procedure which is unlikely to happen in non-experimental situations. Although considerable accurate predicted models of intra-muscular temperature have been developed in the literature, such predictions are probably not practical during most clinical treatments thus the applicability is poor. Another possible issue is that the assessor taking TMG recordings was not blinded to the recovery strategy. However, considering that TMG measurements don't rely on voluntary contraction and that the protocol was performed identically after each condition, we don't think this has caused a bias. Finally, in this study we hypothesised that changes observed in muscle contractile properties seem to favour short-term recovery after hot-water immersion; however, we cannot conclude that this results in better exercise performance since we did not add a post-recovery exercise assessment. Therefore, future investigations are warranted to determine whether an increase in Dmr and Vdr are indicate of better performance.

In conclusion, our study found out that after a damaging bout of exercise, HWI resulted in a higher Dmr than CWI immediately post-recovery, but showed no superiority comparing to passive resting while velocity of contraction was enhanced after HWI comparing to both CWI and passive resting immediately after and at 15 and 45 minutes after.

Disclosure statement

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ORCID

Esther Mur-Gimeno

Raquel Sebio-Garcia

http://orcid .org/0000-000 http://orcid .org/0000-0002-7740-0880 2-7167-4737

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