

Abstract

Purpose: this study aimed to (i) examine the effects of hot-water immersion (HWI) on vertical jump performance, lower-limb power, and stretch-shortening cycle responses, and (ii) evaluate temperature-dependent responses by comparing two HWI conditions (40 °C vs. 42 °C). *Methods:* twenty healthy, physically active participants (12 males, 8 females; age: 25.1 ± 2.7 years; BMI: 22.6 ± 1.1 kg/m²) completed countermovement jump (CMJ) and drop jump assessments before, after, and 15 minutes after a 45-minute water immersion session at either 34 °C (control), 40 °C, or 42 °C in a randomized order. CMJ outcomes included jump height, peak force, and peak power, while drop jump outcomes included jump height, reactive strength index (RSI), and vertical stiffness. *Results:* CMJ height increased following a 45-minute HWI session at both 40 °C and 42 °C ($p < .001$, $d = 1.09$; $p < .001$, $d = 1.77$), with no differences between the two conditions ($p = .515$). Similar improvements were found for peak power and force. At 15 minutes post-immersion, all performance measures returned to baseline and did not differ from the control condition. For the drop jump, a main effect of temperature was observed. HWI at 42 °C significantly increased drop jump height ($p = .004$; $d = 0.71$), whereas 40 °C did not ($p = .205$). RSI increased following both 40 °C ($p = .002$; $d = 0.74$) and 42 °C ($p < .001$; $d = 0.91$) conditions. No significant changes were observed in vertical stiffness. *Conclusion:* both HWI conditions, 40 °C and 42 °C, improved CMJ performance (height, force, and power) and RSI, while only HWI at 42 °C enhanced drop jump height. These effects were transient, returning to baseline within 15 minutes post-immersion.

Keywords: Passive heating; hot-water immersion; vertical jump; explosive contraction; stretch-shortening cycle.

Introduction

Passive increases in muscle temperature have been associated with enhanced muscle contractile function.¹⁻⁴ These improvements appear to follow a dose–response relationship, whereby an increase of approximately 1 °C in muscle temperature can enhance performance by 2–5%, depending on the type and velocity of contraction.⁵ More specifically, these improvements are linked to improvements in rapid contraction responses (i.e., increased rate of torque development) and involuntary contraction properties, particularly electrically evoked, (i.e., increased peak twitch torque and rate of torque development, and decreased half-relaxation time and electromechanical delay) rather than maximal voluntary contraction.^{1-4,6} Consequently, this evidence indicates a potential role of the peripheral mechanisms triggered by passive heating to enhance contractile function, possibly through changes in the elastic properties of the muscle tissue, increasing force transmission during fast contractions. Interestingly, some evoked contractions variables (i.e., peak torque, rate of torque development, and electromechanical delay) demonstrated greater outcomes approximately 15 minutes after a 42 °C hot-water immersion (HWI) session compared to immediately after, suggesting a possible beneficial lag effect of passive heating on muscle contractile properties.^{3,4} However, the lag effects of passive heating have not been further investigated.

The enhancements in rapid contraction properties following passive heating may be explained by an increase in muscle fluid causing an improvement in muscle force transmission. Local muscle blood flow increases linearly with muscle temperature⁷ and can rise by up to 61% after a single session of heat exposure via water perfused suit.⁸ This increase in muscle blood flow, and consequently in muscle fluid, may directly affects the elastic structures of the muscle fibres. During contraction, the muscle fibres tend to compress in the direction of thickness, changing shape and expanding radially when they shorten.⁹ The increased muscle fluid leads to higher passive stiffness, which unloads the muscle during shortening.¹⁰ The incompressible nature of the intracellular fluid decreases the rate of muscle fibre deformation during contraction, acting as a spring, leading to increased forces transmission during muscle contraction.⁹ Hence, the increased internal pressure within muscle cells (spring-like property) induced by passive heating may directly enhance rapid muscle contraction function.¹¹ Notably, while many studies have reported the improvements in faster intrinsic contractile properties after muscle passive heating,^{1-4,6} suggesting muscle power enhancement, these findings are primarily based on isometric contraction measurements. Therefore, studies examining the effects of passive heating on muscle contraction responses during dynamic explosive contractions are still warranted to further understand the real-world applicability of passive heating strategies.

Vertical jump tests, such as the countermovement jump (CMJ) and drop jump, are frequently used in the field of strength and conditioning. These tests rely on the slow and fast components of the stretch-shortening cycle, respectively, and have been shown to be feasible and reliable for assessing acute neuromuscular function responses and adaptations.¹²⁻¹⁴ Furthermore, vertical jump performance is a key indicator in many sports, including basketball, volleyball, football, and track and field events such as the high jump and long jump, and is strongly correlated with muscular strength and sport-specific speed performance.^{15,16} Most explosive human body movements incorporate some degree of countermovement¹⁷ and in high intensity sports, these movements occur naturally due to time constraints limiting large ranges of motion. The stretch-shortening cycle involves an initial muscle-tendon unit lengthening (downward phase) followed by rapid active shortening (upward phase). This cycle incorporates mechanisms such as neuromuscular pre-activation, stretch-reflex contributions, and recoil of elastic stored energy.¹⁸ The storage and utilization of elastic energy during a countermovement is particularly relevant for acute improvements.¹³ Previous studies by Oksa and colleagues¹⁹⁻²¹ suggest a dose–response relationship between muscle temperature and jump height, reporting a

strong positive correlation ($r = 0.906$, $p < 0.001$). This relationship was demonstrated through reductions in performance following passive muscle cooling and subsequent improvements after active rewarming. However, this association has not yet been investigated in the context of passive heating.

Given the above context, passive increases in muscle temperature may enhance muscle power during dynamic contraction beyond the isometric-based findings previously reported. Moreover, passive heating protocols, such as hot baths, may be particularly beneficial in enhancing countermovement by increasing the effectiveness of elastic energy utilization through the spring-like effect, although this hypothesis has not yet been experimentally tested. Therefore, this study aims to examine the effects of lower-limb HWI on vertical jump performance, lower-limb power and stretch-shortening cycle. Additionally, this study aims to explore the temperature-dependent responses of passive heating by comparing two different HWI conditions (40 °C vs. 42 °C), and the lagging effects by testing after the bath and 15 minutes thereafter. We hypothesize that (i) a 45-minute HWI session would improve CMJ and drop jump performance, lower-limb power, and stretch-shortening cycle indicators, (ii) greater improvements would be observed after hot water at 42 °C compared to 40 °C due to temperature-dependent effect, and (iii) additional improvements would occur 15 minutes after the HWI sessions due to a lag effect.

Methods

The study was approved by the Ethics Board of the University (No. 33/2024) in accordance with the Declaration of Helsinki (2013), and all participants gave verbal and written consent.

Participants

Before participation, all volunteers attended an orientation session where they received a detailed explanation of the research design and purpose, testing protocols, potential risks, and risk mitigation strategies. Initially, 22 individuals volunteered for this study, but two withdrew due to injuries unrelated to this study. Then, 20 healthy and physically active participants (12 males, 8 females; age: 25.1 ± 2.7 yrs; stature: 177.1 ± 9.9 cm; body mass: 71.2 ± 8.9 kg; body mass index: 22.6 ± 1.1 kg/m²) completed the study design. Participants were not recruited to this study if they met any of the following criteria: (i) medical conditions contraindicating heat stress (e.g., multiple sclerosis, heart and respiratory diseases); (ii) lower-limb musculoskeletal injury; (iii) use of medication altering thermoregulation; and (iv) pregnancy.

Study design

Participants attended three visits to the exercise physiology laboratory at the University, following a randomized crossover design with a minimum 72-hour washout period between sessions. In each visit, participants underwent one of three water immersion conditions in a randomized order: (i) HWI at 40 °C, (ii) HWI at 42 °C, or (iii) thermoneutral water immersion at 34 °C (control). Upon arrival, participants remained seated at rest for 10 minutes before completing the baseline (Pre) vertical jump performance tests. After each water immersion session, participants took 120 ± 20 seconds to towel dry, change clothes, and put on their shoes before completing the first post-immersion vertical jump tests (Post). A second set of jump tests was completed 15 minutes after the Post measurements (Post-15) (Fig. 1). All participants were instructed to wear the same footwear during each visit. Female participants were scheduled to complete all three testing sessions during the same phase of their menstrual cycle to control for potential hormonal influences on the outcome variables.

Figure 1 – here.

Water immersion protocol

Water immersion sessions were conducted in an inflatable bath with participants submerged to the waist for 45 minutes. The target temperatures ($40^{\circ}\text{C}^{22,23}$ and $42^{\circ}\text{C}^{3,4}$) were selected based on previous studies demonstrating that these intensities are practical, feasible, safe, and effective for passive heating. In the absence of an external heat pump, water temperature was manually regulated using a 0.1°C accuracy probe (a-lineTM - Anandic, Switzerland) placed in the bath throughout the sessions. Hot water was added if the temperature dropped 0.2°C and cold water was added if it rose 0.2°C from the target temperature. Excess water was removed if it exceeded the waist level, to ensure consistency in immersion depth. To avoid dehydration, participants were allowed to drink water *ad libitum* during the entire sessions, also an electric fan was used on the upper body to improve thermal comfort.

Vertical jump performance assessment

The vertical jump tests were performed under controlled environmental conditions ($23 \pm 2^{\circ}\text{C}$; $42 \pm 5\%$ relative humidity). For the CMJ, participants were instructed to keep their hands on hips during the jump, restricting arm swing to minimize the influence of the upper body on the centre of mass and focusing lower-limb force generation. They performed a rapid downward movement flexing hips, knees and ankles into a semi-squat position followed by an explosive vertical jump where they were instructed to jump as high as possible. Participants completed three vertical jumps with a minimum of 60 seconds interval between each trial, and the best performance was used for future data analysis. The metrics assessed were jump height, lower-limb peak force and peak power using MyJump3 Application.

Drop jump test was assessed using a 30-cm box. Participants stepped off the box (without jumping) landing on the ground where they were orientated to immediately perform a maximal vertical jump, minimizing ground contact time. Similarly, to CMJ test, three drop jumps were performed with a minimum of 60 seconds interval between each trial and the best performance was used for data analysis. The metrics assessed were jump height, reactive strength index and vertical stiffness using MyJump3 Application. A meta-analytic review demonstrated that the MyJump app is a valid and reliable tool for assessing neuromuscular function and explosive power through vertical jump performance.²⁴ The application showed an intraclass correlation coefficient (ICC) of 0.997 for CMJ height and exhibited a near-perfect correlation with force platform measurements ($r = 0.968^{25}$ and $r = 0.995^{26}$; $p < 0.001$ for both studies). Additionally, it demonstrated high reliability for the reactive strength index during drop jumps (ICC = 0.981^{27}) and vertical stiffness (ICC = 0.972^{28}).

Statistical Analysis

Statistical analyses were conducted using Jamovi software, with data normality assessed via the Shapiro-Wilk test. Due to inter-individual variability in vertical jump performance test across different testing days, changes from pre-immersion values were used as primary outcomes, calculated as the difference between post-water immersion (ΔPost) and 15 minutes post-immersion ($\Delta\text{Post-15}$) values relative to pre-immersion measures. A two-way repeated measures mixed model (time $\times$ temperature) was applied to analyze these changes, followed by a Bonferroni *post hoc* test where applicable. The alpha level was set at 0.05. Additionally, the magnitude of changes is reported using Cohen's *d* effect size ($\pm 95\%$ confidence interval), with thresholds of 0.2 for small, 0.5 for medium, and 0.8 for large effect size. If HWI induced

significant changes in reactive strength index and/or vertical stiffness, correlation analyses were conducted with CMJ and drop jump height. Pearson's correlation coefficient (r) was used for normally distributed data and Spearman's rank correlation (ρ) for non-normal distribution. Correlation strength was categorized as 0 to 0.19 indicating a very weak correlation, 0.2 to 0.39 weak, 0.4 to 0.59 moderate, 0.6 to 0.79 strong, and >0.8 very strong.

Table 1 presents the descriptive statistics for data collected before (Pre), after (Post), and 15 minutes thereafter (Post-15) post-water immersion sessions, shown as mean $\pm$ standard deviation (SD). The inferential statistics are presented in Figure 2, using change scores at Post and Post-15, displayed as estimated marginal means (EMM) $\pm$ 95% confidence intervals (95% CI).

Results

Table 1 – here.

No significant differences were observed in the Pre-intervention values across the water immersion conditions (34 °C, 40 °C, and 42 °C) for CMJ height, peak force and peak power (all, $p > .99$), or for drop jump measures including height ($p > .84$), reactive strength index ($p > .51$), and vertical stiffness ($p > .83$). CMJ height increased following a 45-minute HWI session at 40 °C and 42 °C, with both conditions showing higher values compared to the control (34 °C) ($p < .001$, $d = 1.09$ [0.42, 1.76]; and $p < .001$, $d = 1.77$ [1.04, 2.49]; respectively), but no difference was observed between the 40 °C and 42 °C water temperature conditions ($p = .515$). Following 15 minutes of recovery from post-water immersion sessions (Post-15), CMJ jump height decreased for both, 40 °C ($p = 0.002$; $d = 1.07$ [0.04, 1.74]) and 42 °C ($p < .001$; $d = 1.49$ [0.76, 2.2]) water immersion, with no difference between any water temperature conditions ($p > .963$) at Post-15 (Fig. 2A). Similar responses were observed for changes in lower-limb force and power following HWI at 40 °C and 42 °C (Fig. 2B, C).

Drop jump height showed no interaction effect ($p = .191$) but revealed a significant temperature effect ($p = .005$). *Post hoc* analysis indicated that 42 °C HWI (EMM [95%CI]: 1.20 [0.45, 1.95] cm) induced increases in vertical drop jump height compared to the control condition (-0.50 [-1.24, 0.24] cm) ($p = .004$; $d = 0.71$ [0.26, 1.16]), whereas HWI at 40 °C (0.43 [-0.31, 1.17] cm) did not show differences with either 42 °C ($p = .397$) or 34 °C ($p = .205$) water immersion conditions (Fig. 2D). The reactive strength index measured by drop jump also showed no interaction effect, but significant temperature effect was observed ($p = .166$; $p < .001$; respectively). Reactive strength index increased following 40 °C (0.021 [-0.034, 0.076] A.U.) and 42 °C (0.072 [0.017, 0.127] A.U.) HWI compared to control (-0.097 [-0.152, -0.42] A.U.) ($p = .002$; $d = 0.74$ [0.29, 1.19] and $p < .001$; $d = 0.91$ [0.44, 1.38], respectively), with no changes observed between 40 °C and 42 °C ($p = 0.145$) HWI conditions (Fig. 2E). Lower-limb stiffness remained unchanged after and 15 minutes after 45 minutes of water immersion across all conditions ($p > 0.05$; Fig. 2F).

As no significant changes were observed for vertical lower-limb stiffness or reactive strength index 15 minutes after the post-HWI sessions, correlation analyses were conducted only using the post-immersion changes in reactivation strength index (Δ Post). Across the three water immersion temperature conditions, changes in reactive strength index showed a moderate positive correlation with CMJ height ($r = 0.532$; $p < .001$) and with drop jump height ($\rho = 0.591$; $p < .001$).

Figure 2 – here.

Discussion

A single 45-minute session of HWI at both 40 °C and 42 °C acutely improved CMJ height, lower-limb force and power, and the **reactive strength index during drop jumps**. However, these enhancements are transient, **returning to baseline levels within 15 minutes after the post-HWI tests**. For vertical drop jump height, improvements were observed only following the 42 °C condition, suggesting a potential temperature-dependent effect. No significant changes were found in vertical stiffness following either HWI condition. Although lower-limb peak power and reactive strength index did not differ significantly between the 40 °C and 42 °C HWI conditions post-intervention, the effect sizes compared to the control condition suggest a possible temperature-related response (peak power: $d = 1.15$ [0.50, 1.80] vs. $d = 1.85$ [1.18, 2.52]; reactive strength index: $d = 0.97$ [0.34, 1.60] vs. $d = 1.25$ [0.60, 1.90], respectively). Of note, these findings reflect outcomes following a 45-minute HWI protocol. If the performance benefits are indeed temperature-dependent, longer HWI sessions may elicit greater improvements. Rodrigues et al.²⁹ demonstrated in a similar cohort of healthy young active adults ($n = 30$; 25 ± 5 years) that vastus lateralis muscle temperature continues to rise during 42 °C HWI up to 83.5 ± 6 minutes, when it reaches a plateau, and peak at 39.0 ± 0.1 °C. After 45 minutes HWI, muscle temperature had reached 38.3 ± 0.3 °C.

Thermal stress responses and vertical jump performance

Passive hyperthermia reduces voluntary activation to the working muscles due to alterations in neural drive;^{1,2} however, this impairment is primarily driven by elevated core temperature rather than local muscle temperature.⁴ Specifically, reductions in neural drive transmission tend to occur when core temperature exceeds 38.5 °C.^{2,6} Therefore, the HWI protocols employed in this study, where only the lower limbs are immersed in water, are unlikely to have negatively affected voluntary muscle activation, as 45 minutes of HWI at 42 °C raises core temperature only to approximately 38.3 ± 0.2 °C.²⁹ The present findings support our first hypothesis that passive increases in muscle temperature via HWI would enhance CMJ and drop jump performance, lower-limb power, and stretch-shortening cycle function. However, our second hypothesis, predicting a temperature-dependent effect, was only partially supported, as it was confirmed solely for drop jump height (Fig. 2D). The third hypothesis, related to a lag effect in performance enhancement, was not supported by any of the variables measured. Previous studies^{3,4} have reported lag effects in intrinsic contractile responses following a 90-minute HWI at 42 °C. It is possible that the present 45-minute protocol did not elicit sufficient increases in muscle temperature to induce this delayed benefit, or that such effects are limited to evoked rather than voluntary explosive contractions. In either case, a single 45-minute HWI session acutely enhances vertical jump performance metrics, but these improvements are transient.

Countermovement vertical jump performance and stretch-shortening cycle behaviour

Although this study did not directly assess specific muscle contraction mechanisms or measure muscle temperature, it is reasonable to suggest that the acute improvements observed following HWI stem from neuromuscular changes induced by increased muscle temperature. The neuromuscular mechanisms likely underpinning these enhancements are discussed below, focusing on muscle slack, the stretch-shortening cycle, and intrinsic contractile properties.

The reactive strength index, defined as the ratio between flight time and contact time during a drop jump, reflects the performance of the lower-limb stretch-shortening cycle.³⁰ The stretch-shortening cycle was initially defined as occurring when a muscle is actively stretched (eccentric contraction) prior to active shortening (concentric contraction).³¹ However, debate persists regarding the muscle actions involved in the downward phase of a jump. The muscle-tendon unit lengthening during the downward phase is mostly passive and occurs primarily, but

not exclusively, in monoarticular muscles.³² Moreover, studies have reported fascicle shortening^{32,33} or isometric actions³⁴ during the downward phase, suggesting minimal or no eccentric fascicle action.¹² Despite the uncertainty regarding eccentric muscle activation, the countermovement action is strongly linked to elastic energy utilization. Reduced muscle slack and enhanced unloading may allow for greater elastic energy storage during maximal CMJ and drop jumps.¹² In this study, both CMJ and drop jump heights improved following HWI, with moderate positive correlations observed between changes in reactive strength index across the water immersion conditions ($r = 0.532$ and $\rho = 0.591$, respectively). These findings suggest that the performance enhancements likely reflect increased elastic energy utilization and improved muscle contraction efficiency. The elevated intracellular fluid and internal pressure resulting from passive heating may enhance the spring-like behavior of muscles during stretch-shortening cycle actions, thereby contributing to the observed gains in countermovement performance.

Apart from the decreased muscle slack and improved elastic energy utilisation, the stretch-shortening cycle also involves neuromuscular pre-activation and stretch-reflex components.¹⁸ It has been reported that ballistic movements such as vertical jumping already require maximal motor unit activation, regardless of the muscle shortening velocity during the concentric phase.³⁵ However, the selective recruitment of high-threshold motor units, increased firing frequency, and improved recruitment efficiency can further enhance rapid contraction responses and ballistic performance,³⁶ potentially influenced by stretch-reflex mechanisms.

The stretch reflex is triggered when muscle fibres are rapidly lengthened, activating muscle spindles and leading to the recruitment of additional motor units or increased discharge rates.^{37,38} Although muscle spindles are sensitive to the amplitude of muscle fibre lengthening, it remains unclear to what extent the stretch reflex is engaged in muscles spanning the hip, knee, and ankle joints during the downward phase of the CMJ.¹² Nevertheless, muscle spindles are also sensitive to the velocity of lengthening, with higher velocities eliciting stronger reflex responses.³⁹ Consequently, drop jumps may have greater stretch reflex benefits compared to CMJs. In the present findings, CMJ height did not differ significantly between HWI conditions (40 °C vs. 42 °C), likely reflecting a lower unloading phase and a slower stretch-shortening cycle. In contrast, for drop jump height — which involves greater unloading and a faster stretch-shortening cycle — only the 42 °C HWI condition produced meaningful improvements. This may indicate that the stretch reflex responses enhancement is temperature dependent. However, the current study does not provide sufficient data to confirm this.

Following the downward phase (active + passive forces), the stored elastic energy relies on rapid concentric activation to enhance vertical jump performance. Thus, a quick buildup of muscle activation is a critical factor.¹² This buildup does not solely refer to the rate of neural activation or synaptic input to the muscles, it also involves the rate of muscle excitation in an active state (i.e., the fraction of actin binding sites available for cross-bridge formation in response to a given stimulation).⁴⁰ Notably, it has been suggested that increased muscle temperature and fluid content following passive heating can facilitate cross-bridge formation by reducing ionic strength and enhancing both calcium kinetics and sensitivity (see Rodrigues et al.¹¹ for a review). Therefore, passive muscle heating may improve countermovement performance and stretch-shortening cycle function primarily through enhanced elastic energy utilisation and improved contractile function.

Although improvements in elastic energy components appear to contribute substantially to the observed increases in CMJ and drop jump performance following passive heating, no significant changes were detected in vertical stiffness during drop jumps. Vertical stiffness represents an individual's overall lower-limb compliance⁴¹ and is calculated as the ratio of peak vertical ground reaction force to centre of mass displacement.⁴² Several factors influence

mechanical stiffness, and vertical stiffness is highly individualised. The optimal stiffness level and the neuromuscular strategies adopted across joints vary between individuals.⁴³ Therefore, the high inter-individual variability in vertical stiffness responses may have **limited** our ability to detect significant changes.

Limitations

This research design was based on the premise that passive increases in muscle temperature can influence vertical jump performance and enhance stretch-shortening cycle responses in a temperature-dependent manner. However, due to equipment limitations, we were unable to directly measure intramuscular temperature (i.e., the endogenous thermal response). Instead, our hypotheses and interpretations were based on the water temperature levels used (i.e., the applied exogenous thermal stress). Moreover, although our findings suggest that HWI is effective in improving vertical jump performance and that fast stretch-shortening cycle actions may exhibit a temperature dose–response relationship, we did not compare these effects to those elicited by an active warm-up. The inclusion of a thermoneutral water immersion condition at 34 °C served to control for the effects of hydrostatic pressure. However, the present design does not allow for conclusions regarding whether HWI is superior or comparable to traditional warm-up routines.

Practical applications and directions for future studies

This study employed HWI to the waist level due to its practicality and efficiency. Whole-body passive heating, using either air (e.g., sauna) or water immersion, accelerates increases in core temperature^{2,6,44} to levels that may impair voluntary activation. By immersing only the lower limbs, the upper body remains free from thermal stress, allowing a greater surface area for heat dissipation while muscle temperature continues to rise;²⁹ thereby, improving body thermodynamics and participant's thermal comfort. While microwave diathermy devices are considered the most effective method for rapidly increasing muscle temperature,⁴⁵ they are limited to heating single muscle **groups** per session. In contrast, HWI induces thermal stress across multiple muscles simultaneously, making it more suitable for targeting improvements in dynamic, multi-joint movements such as vertical jumping.

Although this study did not measure muscle temperature, blood flow, or intracellular fluid shifts to directly support the proposed mechanisms behind enhanced spring-like responses, or neuromuscular function such as buildup muscle activation and stretch reflex responses, it provides novel evidence on the effects of passive heating on dynamic muscle contractions. Passive increases in muscle temperature through HWI enhances vertical jump performance, likely due to improved muscle contractile function and stretch-shortening cycle efficiency. These physiological changes may offer performance benefits across various sports that require explosive power, such as long jumping, sprinting, Olympic weightlifting, and team sports involving rapid changes of direction. Furthermore, endurance sports that involve repetitive countermovement actions, such as running, may also benefit from the effects of HWI.

Previous research has reported a relationship between a higher reactive strength index and improved running economy.⁴⁶ Therefore, it is plausible that HWI may enhance running economy by improving stretch-shortening cycle function. However, further research is needed to explore the effects of passive heating on performance in sport-specific explosive tasks and running economy. Moreover, it would be valuable to compare HWI interventions with, or in combination to, traditional active warm-up strategies to assess their relative effectiveness and practicality in sport-specific contexts. Understanding the distinctions between passive and

active heating modalities may provide insights into optimal warm-up practices for enhancing sport performance.

Conclusion

A 45-minute HWI at both 40 °C and 42 °C resulted in improved vertical jump performance. These enhancements following HWI are most likely attributable to increased elastic energy utilisation during the stretch-shortening cycle and improved intrinsic contractile properties. While both HWI protocols were effective, the 42 °C condition elicited greater improvements in drop jump height, suggesting a more pronounced effect on fast stretch-shortening cycle actions. These performance benefits may be temperature-dependent but do not have a lag effect.

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Figure captions:

Figure 1 – Study design.

Figure 2 – Changes in vertical jump height (A), lower-limb force (B) and lower-limb power (C) measured by countermovement jump (CMJ) after (Post) and 15 minutes after (Post-15) 45 minutes of water immersion at 34 °C, 40 °C and 42 °C. Also, changes in vertical jump height (D), reactive strength index (RSI) (E) and lower-limb stiffness (F) measured by drop jump test. The changing scores (Δ) are presented as estimated marginal means $\pm$ 95% confidence interval. ‡ statistical difference between water immersion conditions; * statistical difference between time points within water immersion conditions; $p < 0.05$.

Table 1. Descriptive statistics for countermovement jump and drop jump parameters measured before (Pre), after (Post), and 15 minutes after (Post-15) the water immersion sessions at 34 °C, 40 °C and 42 °C. Data are presented as mean $\pm$ standard deviation.