

Hydrogen-rich water supplementation exhibits dose- and age-dependent effects on delayed-onset muscle soreness in professional soccer players

JAKUB KREJČÍ¹, MICHAL BOTEK², SHIGEO OHTA³, KLÁRA BOTKOVÁ⁴, ANDREW J. MCKUNE⁵

^{1,2}Department of Natural Sciences in Kinanthropology, Faculty of Physical Culture, Palacký University Olomouc, Olomouc, CZECHIA

³Department of Neurology Medicine, Graduate School of Medicine, Juntendo University, Tokyo, JAPAN, and Department of Cell Biology, Graduate School of Medicine, Nippon Medical University, Tokyo, JAPAN

⁴Department of Adapted Physical Activities, Faculty of Physical Culture, Palacký University Olomouc, Olomouc, CZECHIA

⁵Faculty of Health, UC-Research Institute for Sport and Exercise, University of Canberra, Canberra, AUSTRALIA, and Discipline of Biokinetics, Exercise and Leisure Sciences, School of Health Sciences, University of KwaZulu-Natal, Durban, SOUTH AFRICA

Published online: September 30, 2025

Accepted for publication: September 15, 2025

DOI:10.7752/jpes.2025.09201

Abstract

Problem Statement: Effective inter-match recovery plays a crucial role in preserving performance and preventing injuries in well-trained soccer players. In this context, molecular hydrogen has attracted increasing attention in sports science due to its selective antioxidative, anti-inflammatory, and cell-signaling properties that may facilitate recovery. Among the various administration methods, hydrogen-rich water (HRW) appears to be the most common and practical form of supplementation. Nevertheless, the optimal dosage remains unclear, as recent evidence suggests that both the timing and amount of molecular hydrogen intake may influence recovery outcomes. Furthermore, its effectiveness appears to be modulated by individual characteristics such as age, highlighting the need for further targeted research. **Approach:** Professional soccer players were randomly assigned into two groups. Group 1 ($n = 20$, age 24.8 ± 4.3 years) received two 420-ml packs of hydrogen-rich water (HRW) or placebo, one prior to and one during halftime of a large-sided game. Group 2 ($n = 18$, age 25.4 ± 5.1 years) received two additional packs after the game. Each group participated in two games, with HRW and placebo administration randomized across games. Delayed-onset muscle soreness (DOMS) was assessed 24 hours post-game using a 100-mm horizontal visual analogue scale. The effect of HRW administration on DOMS was assessed in a dose- and age-dependent manner. **Results:** In younger players (<25 years), both two packs (placebo: 58 ± 5 mm, HRW: 42 ± 10 mm, $p = 0.004$) and four packs (placebo: 58 ± 11 mm, HRW: 41 ± 7 mm, $p = 0.004$) of HRW resulted in similarly significant reductions in DOMS. In contrast, among older players (≥ 25 years), two packs of HRW did not significantly reduce DOMS (placebo: 60 ± 15 mm, HRW: 54 ± 20 mm, $p = 0.19$), whereas four packs produced a significant reduction (placebo: 64 ± 10 mm, HRW: 42 ± 9 mm, $p = 0.004$). **Conclusions:** These findings suggest that a higher dose of HRW may be necessary to effectively reduce DOMS in older compared with younger soccer players. Therefore, both dosage and player age should be considered when implementing HRW as a novel recovery strategy in professional soccer to optimize its benefits for reducing muscle soreness and enhancing post-game recovery. Moreover, incorporating higher HRW doses in older players could represent a valuable addition to existing recovery protocols, as advancing age is associated with diminished antioxidant capacity, slower resolution of inflammation, and prolonged recovery.

Key Words: molecular hydrogen, muscle pain perception, exercise, recovery, visual analogue scale

Introduction

Effective recovery between matches is critical for maintaining performance and health in well-trained soccer players (Dupont et al., 2015; Nédélec et al., 2012). Consequently, there is growing interest in the development of novel post-exercise recovery strategies (Altarriba-Bartes et al., 2020; Terrados et al., 2019). It is well established that many physical actions performed by soccer players during a match involve eccentric muscle contractions which contribute to exercise-induced muscle damage and the subsequent development of delayed-onset muscle soreness (DOMS) (Nédélec et al., 2012). In this context, there is evidence that exercising under conditions of DOMS is associated with a higher risk of muscle injury and also contributes to impaired muscle function and delayed recovery, factors that can further impair performance and increase susceptibility to secondary injuries (Wei et al., 2025). Traditionally, DOMS is defined as a feeling of discomfort that emerges 8–10 hours after strenuous or unfamiliar exercise (Balnave & Thompson, 1993; Eston et al., 1996). It is most noticeable in skeletal muscle between 24–48 hours after exercise and usually resolves within the next few days (Cheung et al., 2003). The pathophysiology of DOMS appears to be multifactorial, involving both mechanical

and metabolic stress at the cellular level (Pyne, 1994) as well as an inflammatory reaction to connective tissue or muscle damage (Cheung et al., 2003; Smith, 1991). Furthermore, several studies have linked DOMS with apoptosis (Hotfiel et al., 2018) and to elevated oxidative stress associated with increased production of reactive oxygen and nitrogen species (Pyne, 1994; Toumi & Best, 2003).

DOMS is commonly assessed using a visual analogue scale (VAS) in elite soccer players (Akenhead & Nassis, 2016; Fonseca et al., 2017). Monitoring DOMS using VAS can help determine the efficacy of recovery strategies. The VAS is considered a highly reliable and methodologically sound tool for detecting clinically meaningful changes in muscle soreness (Bijur et al., 2001; Gallagher et al., 2002). Moreover, plasma concentrations of the pro-inflammatory cytokine interleukin-6 and creatine kinase, an indirect marker of muscle damage, have been significantly correlated with VAS scores 24 and 48 hours after a downhill run (Kawamura et al., 2018).

Molecular hydrogen (H_2) has been identified as a potent and selective antioxidant capable of attenuating cytotoxic hydroxyl radicals (Ohsawa et al., 2007; Ohta, 2014, 2023). In biological systems, H_2 administration has demonstrated to anti-inflammatory (Ara et al., 2018), anti-apoptotic (Ohta, 2014), and cell-signalling effects (Slezak et al., 2021), thereby facilitating post-exercise recovery across various exercise modalities (Botek et al., 2022; Kawamura et al., 2016; Sládečková et al., 2024; Zhou et al., 2023). However, the dose-response relationship of H_2 remains poorly understood, particularly in the context of sports medicine (Kawamura et al., 2020; Ostojic, 2015). While some animal studies reported no dose-response effect of H_2 administration (Fujita et al., 2009; Ito et al., 2012; Ohno et al., 2012), a recent review indicated a dose-response effect of H_2 in *in vitro* models (Ichihara et al., 2015). In sports medicine, evidence for a dose-response effect of H_2 is inconsistent (Botek et al., 2020; Kawamura et al., 2020; Ostojic, 2015; Timón et al., 2021). These discrepancies may result from variations in H_2 administration strategies across studies, including differences in timing (before, during, or after exercise) and delivery methods, which vary in practicality, bioavailability, and clinical applicability (Kawamura et al., 2020; Ohta, 2023). Oral ingestion of hydrogen-rich water (HRW) is the most common and suitable method for long-term use, while inhalation of low concentrations of H_2 gas ($\leq 4\%$) is a rapid and effective route that is particularly relevant in acute medical situations, rather than in sports context. H_2 bathing, which involves immersion in HRW, offers non-invasive transdermal absorption and has shown potential for reducing post-exercise muscle soreness (Kawamura et al., 2016). Other strategies are also being explored, such as transdermal application, hydrogen-releasing tablets, or nanoparticle-based systems (Ohta, 2023). However, the coexistence of these different methods of administration complicates the comparison of studies and makes it difficult to reliably assess the dose-response relationship (Kawamura et al., 2020).

Although the optimal age for peak performance in elite soccer players is typically between 25 and 27 years (Dendir, 2016), professional careers can extend up to 40 years of age (Lorenzo-Martínez et al., 2020). Increasing player age has been proposed as a factor that may influence the time course of post-match recovery (Nédélec et al., 2012). Specifically, one of the key changes is a diminished capacity to suppress inflammation, with older individuals frequently exhibiting prolonged elevations in pro-inflammatory cytokines such as interleukin-6 and tumor necrosis factor alpha, a phenomenon often referred to as inflammaging (Sellami et al., 2021). In parallel, the regulation of oxidative stress becomes less effective due to reduced activity of endogenous antioxidant defense systems, making older athletes more susceptible to exercise-induced reactive oxygen species and associated tissue damage (Kregel & Zhang, 2007). In addition, aging muscles exhibit increased activation of redox-sensitive signaling pathways such as NF- κ B and increased lipid peroxidation, which promotes proteolysis, and contributes to muscle fiber apoptosis in response to strenuous physical activity (Radák et al., 2004). Accordingly, it is important to assess whether age serves as a moderator of the dose-response relationship of H_2 . In the present study, we hypothesized that: 1) a higher dosage of HRW would result in a greater attenuation of DOMS compared to a lower dosage, and 2) the effect of HRW relative to placebo would be moderated by age.

Materials & methods

Participants

This study included 38 soccer players from two soccer clubs playing in the Czech First League (Table 1). The inclusion criteria were as follows: 1) being a member of a soccer A-team except for goalkeepers, 2) having undergone testing in our laboratory no more than 3 months before the experimental protocol, and 3) being free of any health problems during the entire experimental protocol. This study received approval from the Ethics Committee of the Faculty of Physical Culture, Palacký University Olomouc (reference number: 75/2017) and was conducted in accordance with the principles of the Declaration of Helsinki. Prior to the commencement of the experiment, all participants were informed about the study objectives and measurement procedures. Participation was voluntary, and all players provided written informed consent.

Table 1. Characteristics of the studied groups

Variable	Group 1	Group 2	p
Sample size	20	18	
Age (years)	24.8 $\pm$ 4.3	25.4 $\pm$ 5.1	0.64
Body height (cm)	182.9 $\pm$ 7.0	182.3 $\pm$ 5.4	0.54
Body mass (kg)	76.6 $\pm$ 6.2	75.5 $\pm$ 6.1	0.46

BMI (kg·m ⁻²)	22.9 ± 1.3	22.7 ± 1.0	0.85
Body fat (%)	10.8 ± 2.7	11.1 ± 2.3	0.98
VO ₂ max (ml·kg ⁻¹ ·min ⁻¹)	54.6 ± 2.8	55.2 ± 5.2	0.73
Pmax (W)	6.32 ± 0.30	6.36 ± 0.45	0.85
CMJ (cm)	46.4 ± 4.5	45.5 ± 5.9	0.61
Absolute dose (μmol)	378	756	
Relative dose (μmol·kg ⁻¹)	4.97 ± 0.43	10.08 ± 0.84	<0.001

Group 1 = group that ingested two packs of water, Group 2 = group that ingested four packs of water, p = significance of Mann-Whitney U test, BMI = body mass index, VO₂max = maximal oxygen consumption, Pmax = maximal power, CMJ = countermovement jump, absolute dose = amount of molecular hydrogen administered to one subject, relative dose = hydrogen dose per kg of body mass.

Experimental design

The study employed a randomized, double-blind, placebo-controlled design with a mixed parallel-group and crossover structure. The study protocol is illustrated in Fig. 1. Maximal oxygen consumption, maximal power output, and countermovement jump height were measured in our laboratory as part of routine testing following procedures published elsewhere (Botek et al., 2016, 2021). These laboratory diagnostics were not part of the present study and are provided for descriptive purposes only.

The two soccer teams were randomly allocated into two groups, each subjected to distinct dosing protocols. Group 1 received one pack of water immediately before the game and another at the end of halftime. Group 2 received the same two packs as Group 1, plus an additional two packs within 60 minutes post-game, totalling four packs. Due to logistical constraints, the allocation of the dosing strategy was not blinded to subjects or researchers. Within each group, players were further randomized to AB or BA sequences, indicating the order of HRW and placebo administration. Randomization ensured a balanced number of AB and BA sequences and was performed using the randperm function (MATLAB R2020a, MathWorks, Natick, USA). Packs were labelled as batch A or B, and the manufacturer maintained the blinding of HRW versus placebo until the completion of the experimental protocol and statistical analysis, thereby ensuring double-blinding of the crossover phase.

At the beginning of the first session, anthropometric measures were obtained. Body mass and height were determined using a SOEHNLE 7307 digital scale (Leifheit, Nassau, Germany) and body fat was determined using a BC-418 MA bioimpedance device (Tanita, Tokyo, Japan). Each group then played a large-sided game in an 11 vs. 11 configuration on a grass soccer pitch (105 × 68 m). Goalkeepers and players who missed laboratory testing were excluded, resulting in final sample sizes of 20 and 18 for Group 1 and 2, respectively. The game lasted 90 minutes, divided into two 45-minute halves within a 15-minute halftime break. Each player was asked to rate muscle soreness on a VAS, 24 hours after the end of the game. The second game was conducted after a one-week washout period, during which the game was repeated with the AB and BA sequences.

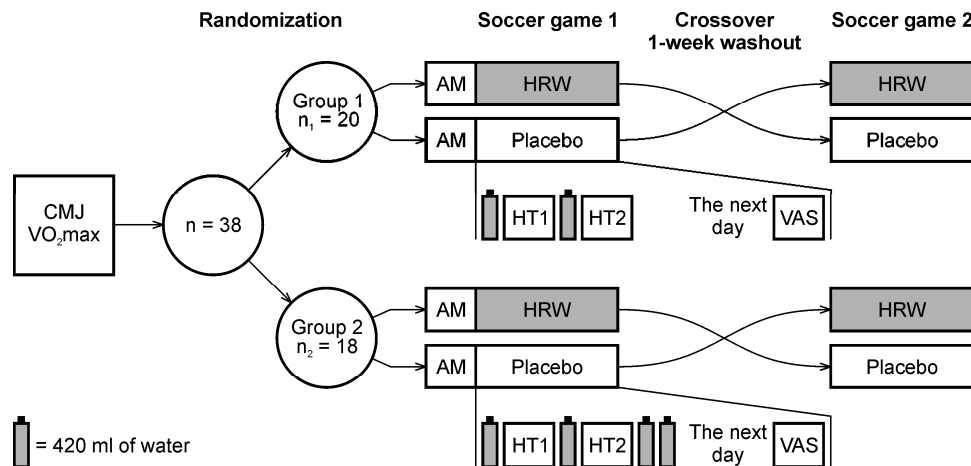


Figure 1. Experimental protocol of the study. CMJ = countermovement jump measurement, VO₂max = maximal oxygen consumption measurement, Group 1 = group that ingested two packs of water, Group 2 = group that ingested four packs of water, AM = anthropometric measurement, HRW = hydrogen-rich water, HT1 = the first halftime, HT2 = the second halftime, VAS = visual analogue scale.

Hydrogen-rich water and placebo preparation

Hydrogen-rich water (HRW) was supplied in 420-ml plastic-aluminium packs with a gas-tight cap (Aquastamina-R, Nutristamina, Ostrava, Czech Republic). According to the manufacturer, HRW was produced by infusing H₂ into drinking water under high pressure. Aquastamina-R contained no additives other than H₂. The placebo was provided by the same manufacturer and was prepared using an identical procedure and packaging, except that the H₂ infusion step was omitted. Because H₂ is colourless, odourless, and tasteless

(Kawamura et al., 2020), HRW and placebo were indistinguishable by human sensory perception. The type of water (HRW or placebo) was indicated on the packaging using different batch labels (A or B). The physicochemical characteristics of HRW and placebo were as follows: pH 7.6/7.5, oxidation-reduction potential $-634/+187$ mV, and temperature $21/21$ °C, as measured using a pH/ORP/temperature meter (AD14, Adwa Instruments, Szeged, Hungary). The concentration of dissolved H_2 was $1.0/0.0$ ppm, determined using the H2Blue reagent method (H2 Sciences, Henderson, NV, USA).

Visual analogue scale

The VAS consisted of a 100-mm horizontal-line printed on paper, anchored at 0 mm (no pain) and 100 mm (worst imaginable pain). Participants were instructed to indicate the intensity of their perceived muscle soreness by placing a mark along the line. To standardize muscle activation prior to assessment, players performed a parallel squat and were then asked to rate perceived muscle soreness for both legs simultaneously on the VAS. The marked sheets were collected and the ratings were measured by a researcher using a ruler to determine the distance (in millimetres) from the 0 mm anchor to the participant's mark, representing the level of soreness.

Statistical analysis

Data are expressed as mean $\pm$ standard deviation. Between-group differences in players characteristics were assessed using the Mann-Whitney U test. Within each group, VAS scores for HRW were compared with placebo using the Wilcoxon signed rank test. For each player, the change in VAS was calculated as $\Delta = \text{Placebo} - \text{HRW}$, and these changes were subsequently compared between groups (two versus four packs of HRW) using the Mann-Whitney U test. To evaluate whether age moderated the VAS, players were divided into two subgroups based on median age. The same statistical procedures were then applied to each subgroup (younger and older players) as used for the full sample. The significance level was set at $\alpha = 0.05$. Statistical analyses were performed using MATLAB R2020a.

Results

The characteristics of the study groups are presented in Table 1. No significant differences were observed between the groups (all $p \geq 0.46$), except for the dose of H_2 relative to body mass, which was significantly different ($p < 0.001$).

The effects of HRW compared to placebo on DOMS are shown in Fig. 2. In the group receiving two packs of HRW, DOMS was significantly reduced (placebo: 59 ± 11 mm, HRW: 48 ± 17 mm, $p = 0.002$). Similarly, in the group receiving four packs of HRW, DOMS was significantly reduced (placebo: 61 ± 11 mm, HRW: 42 ± 8 mm, $p < 0.001$). Although the reduction in DOMS was greater with four packs ($\Delta = 19 \pm 13$ mm) compared to two packs ($\Delta = 11 \pm 12$ mm), this difference did not reach statistical significance ($p = 0.092$).

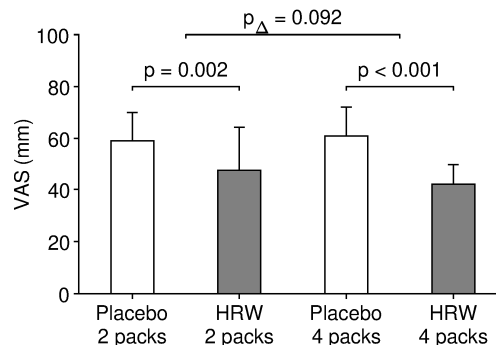


Figure 2. The effect of hydrogen-rich water on delayed onset muscle soreness. Data are presented as means and standard deviations. VAS = visual analogue scale, HRW = hydrogen-rich water, p = significance of Wilcoxon signed rank test for comparison of VAS between waters, p_{Δ} = significance of Mann-Whitney U test for comparison of VAS reductions between groups.

To explore the moderating effect of age, the full sample was divided into two subgroups based on the median age of 24.5 years, as shown in Fig. 3. Among younger players (<25 years), both two packs (placebo: 58 ± 5 mm, HRW: 42 ± 10 mm, $p = 0.004$) and four packs (placebo: 58 ± 11 mm, HRW: 41 ± 7 mm, $p = 0.004$) of HRW resulted in similarly significant reductions in DOMS. The difference in reduction between two packs ($\Delta = 16 \pm 12$ mm) and four packs ($\Delta = 17 \pm 13$ mm) was not statistically significant ($p = 0.95$). In contrast, among older players (≥ 25 years), two packs of HRW did not significantly reduce DOMS (placebo: 60 ± 15 mm, HRW: 54 ± 20 mm, $p = 0.19$). However, four packs of HRW produced a significant reduction (placebo: 64 ± 10 mm, HRW: 42 ± 9 mm, $p = 0.004$). The difference in reductions between two packs ($\Delta = 6 \pm 11$ mm) and four packs ($\Delta = 22 \pm 12$ mm) was statistically significant ($p = 0.016$).

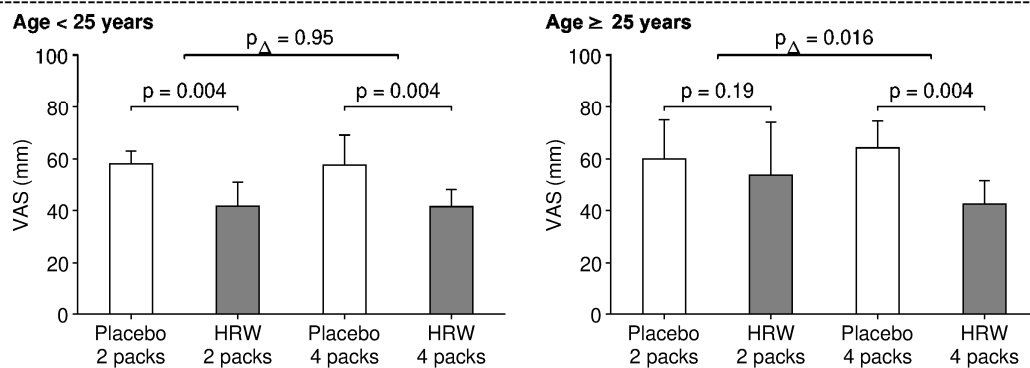


Figure 3. The effect of hydrogen-rich water on delayed onset muscle soreness by age. Data are presented as means and standard deviations. VAS = visual analogue scale, HRW = hydrogen-rich water, p = significance of Wilcoxon signed rank test for comparison of VAS between waters, p_{Δ} = significance of Mann-Whitney U test for comparison of VAS reductions between groups.

Discussion

The key findings of this study are as follows: 1) HRW intake significantly alleviated DOMS 24 hours after a large-sided game compared to placebo; and 2) among younger players, the effect of HRW was not dose-dependent, whereas in older players, twice the dose of HRW resulted in a more pronounced reduction in DOMS compared to the lower dose.

Previous research has shown that H_2 , known for its antioxidative and anti-inflammatory properties (Slezak & Kura, 2024), may help attenuate DOMS following various exercise modalities. However, the precise aetiology of DOMS remains a topic of ongoing debate. While exercise-induced muscle damage, accompanied by inflammation and oxidative stress, is widely considered a key contributing factor, it is not the sole mechanism involved (Peake et al., 2017). HRW intake (3×420 ml) has been shown to significantly reduce DOMS 24 hours after strenuous strength training (Botek et al., 2021). Similarly, a 20-minute H_2 bath administered following a 30-minute downhill run (-8% slope, 75% $VO_{2\max}$ intensity) significantly attenuated DOMS during the first two days post-exercise (Kawamura et al., 2016). Additionally, the recovery-promoting effects of HRW have recently been reported in elite fin-swimmers (Sládečková et al., 2024). Fin-swimmers who consumed 6300 ml of HRW over four days, experienced significantly lower DOMS 24 hours after a training day that included two vigorous training sessions.

The VAS results in the present study can be interpreted based on the minimum clinically significant difference for VAS scores (Kelly, 2001). For moderate pain (31 to 69 mm), this threshold has been established at 14 mm (Kelly, 2001). Among older players (>25 years), a higher dose of HRW (four packs) produced a clinically significant reduction in DOMS (22 mm), whereas a lower dose (two packs) did not (6 mm). In contrast, younger players (≤ 25 years), experienced clinically significant reductions in DOMS with both doses (two packs: 16 mm, four packs: 17 mm).

To the best of our knowledge, this is the first study to demonstrate that age moderates the dose-response effect of HRW in reducing DOMS. While the importance of considering age in H_2 research has been acknowledged (Sim et al., 2020), the combined influence of age and dosage has not previously been investigated. Sim et al. (2020) examined antioxidant responses to a four-week intake of 1.5 L of HRW per day in healthy adults aged 20–59 years and found that the health-benefits of HRW were more pronounced in older individuals (≥ 30 years) compared to younger individuals (< 30 years). Previous research has also shown that increasing age is associated with diminished capacity to resolve inflammation (Sellami et al., 2021), regulate oxidative stress (Kregel & Zhang, 2007), and mitigate exercise-induced cellular stress responses such as elevated LIPOX level and NF- κ B activation (Radák et al., 2004). Based on these findings, we propose that increasing the dose of HRW may be particularly important for older athletes to achieve clinically meaningful reductions in DOMS.

It is important to emphasize that the doubling of the total HRW dose was achieved by administering an additional two packs of water after the game, during the recovery period. This approach was chosen to avoid having the players consume two packs before the game and two packs at halftime, due to concerns about potential gastrointestinal discomfort associated with ingesting a high volume of water in a short time frame. From a methodological standpoint, this study not only varied the dose of HRW but also altered the timing of its administration. Timing is considered a critical factor that may influence the physiological effects of H_2 . Kawamura et al. (2020) recommended repeated exposure to H_2 to enhance its physiological effects, noting that breath H_2 concentration peak within 10–15 minutes following HRW ingestion and returned to baseline within approximately 45 minutes (Shimouchi et al., 2012). Our findings suggest that HRW consumption before the game (420 ml) and at halftime (420 ml) exerted a notable preconditioning effect on the development of DOMS. Importantly, the addition of a post-game HRW dose (2×420 ml) further alleviated DOMS, particularly among older players, highlighting the potential benefit of extending H_2 exposure into the recovery period.

This study has several limitations: First, for logistical reasons, the H₂ dose was kept constant within each group and was not normalized to individual body mass. Second, workload before, during, and after the games, including during the washout period, was not monitored, and biomarkers of muscle damage, oxidative stress, and inflammation were not assessed across the two games. Collecting this information could have provided valuable insights into the mechanisms by which H₂ reduces DOMS and helped to better understand individual variability in response to H₂ supplementation.

Conclusions

HRW appears to be a promising hydration strategy for reducing DOMS in professional soccer players. Both two and four packs of 420 ml HRW, administered during or after a large-sided soccer game, significantly reduced DOMS 24 hours after the game. Importantly, when accounting for player age, the higher dose of HRW was more effective in alleviating DOMS among older players (≥ 25 years) compared to younger players (< 25 years) suggesting that age may moderate the dose-response relationship of HRW. From a practical point of view, HRW can be incorporated into standard post-match recovery protocols to alleviate muscle soreness and accelerate readiness for subsequent training sessions or competitions. Coaches and conditioning trainers should tailor HRW dosages to the age of players, allowing for more individualized and effective recovery strategies. For older players, higher doses of HRW could be particularly useful in facilitating recovery during busy match schedules, reducing the risk of accumulated fatigue and overuse injuries. More broadly, the implementation of HRW offers a simple, safe, and cost-effective tool that complements existing recovery methods and supports performance maintenance and injury prevention in professional soccer.

Conflict of interest

Michal Botek serves as an external research consultant for H2 Global Group (Ostrava, Czechia). Shigeo Ohta is the director of H2 WATER JAPAN (Tokyo, Japan) and a member of H2 Global Group (Ostrava, Czechia), companies involved in molecular hydrogen related research and production. The other authors declare that there is no conflict of interest.

Acknowledgments

This research was funded by a grant IGA_FTK_2023_012 from the Palacký University Olomouc.

References

- Akenhead, R., & Nassis, G. P. (2016). Training load and player monitoring in high-level football: Current practice and perceptions. *International Journal of Sports Physiology and Performance*, 11(5), 587–593. <https://doi.org/10.1123/ijsp.2015-0331>
- Altarriba-Bartes, A., Peña, J., Vicens-Bordas, J., Milà-Villaroel, R., & Calleja-González, J. (2020). Post-competition recovery strategies in elite male soccer players. Effects on performance: A systematic review and meta-analysis. *PLOS One*, 15, 1–20. <https://doi.org/10.1371/journal.pone.0240135>
- Ara, J., Fadriqela, A., Ahmed, F., Bajgai, J., Sajo, M. E. J., Lee, S. P., Kim, T. S., Jung, J. Y., Kim, C. S., Kim, S. K., Shim, K. Y., & Lee, K. J. (2018). Hydrogen water drinking exerts antifatigue effects in chronic forced swimming mice via antioxidative and anti-inflammatory activities. *BioMed Research International*, 2018, 1–9. <https://doi.org/10.1155/2018/2571269>
- Balnave, C. D., & Thompson, M. W. (1993). Effect of training on eccentric exercise-induced muscle damage. *Journal of Applied Physiology*, 75(4), 1545–1551. <https://doi.org/10.1152/jappl.1993.75.4.1545>
- Bijur, P. E., Silver, W., & Gallagher, E. J. (2001). Reliability of the visual analog scale for measurement of acute pain. *Academic Emergency Medicine: Official Journal of the Society for Academic Emergency Medicine*, 8(12), 1153–1157. <https://doi.org/10.1111/j.1553-2712.2001.tb01132.x>
- Botek, M., Khanna, D., Krejčí, J., Valenta, M., McKune, A., Sládečková, B., & Klimešová, I. (2022). Molecular hydrogen mitigates performance decrement during repeated sprints in professional soccer players. *Nutrients*, 14, 1–10. <https://doi.org/10.3390/nu14030508>
- Botek, M., Krejčí, J., McKune, A. J., & Klimešová, I. (2016). Somatic, endurance performance and heart rate variability profiles of professional soccer players grouped according to age. *Journal of Human Kinetics*, 54(1), 65–74. <https://doi.org/10.1515/hukin-2016-0035>
- Botek, M., Krejčí, J., McKune, A. J., & Sládečková, B. (2020). Hydrogen-rich water supplementation and uphill running performance: Effect of athlete performance level. *International Journal of Sports Physiology and Performance*, 15(8), 1193–1196. <https://doi.org/10.1123/ijsp.2019-0507>
- Botek, M., Krejčí, J., McKune, A., Valenta, M., & Sládečková, B. (2021). Hydrogen rich water consumption positively affects muscle performance, lactate response, and alleviates delayed onset of muscle soreness after resistance training. *Journal of Strength and Conditioning Research*, 1–8. <https://doi.org/10.1519/JSC.0000000000003979>
- Cheung, K., Hume, P., & Maxwell, L. (2003). Delayed onset muscle soreness: Treatment strategies and performance factors. *Sports Medicine*, 33(2), 145–164. <https://doi.org/10.2165/00007256-200333020-00005>

- Dendir, S. (2016). When do soccer players peak? A note. *Journal of Sports Analytics*, 2, 89–105. <https://doi.org/10.3233/JSA-160021>
- Dupont, G., Nédélec, M., McCall, A., Berthoin, S., & Maffiuletti, N. A. (2015). Football recovery strategies. *Aspetar Sports Medicine Journal*, 4, 20–27.
- Eston, R. G., Finney, S., Baker, S., & Baltzopoulos, V. (1996). Muscle tenderness and peak torque changes after downhill running following a prior bout of isokinetic eccentric exercise. *Journal of Sports Sciences*, 14(4), 291–299. <https://doi.org/10.1080/02640419608727714>
- Fonseca, R. T., Nunes, R. A. M., Castro, J. B. P., Lima, V. P., Silva, S. G., Dantas, E. H. M., & Vale, R. G. S. (2017). The effect of aquatic and land plyometric training on the vertical jump and delayed onset muscle soreness in Brazilian soccer players. *Human Movement Special Issues*, 18(5), 63–70. <https://doi.org/10.1515/humo-2017-0041>
- Fujita, K., Seike, T., Yutsudo, N., Ohno, M., Yamada, H., Yamaguchi, H., Sakumi, K., Yamakawa, Y., Kido, M. A., Takaki, A., Katafuchi, T., Tanaka, Y., Nakabeppu, Y., & Noda, M. (2009). Hydrogen in drinking water reduces dopaminergic neuronal loss in the 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine mouse model of Parkinson's disease. *PLOS One*, 4, 1–10. <https://doi.org/10.1371/journal.pone.0007247>
- Gallagher, E. J., Bijur, P. E., Latimer, C., & Silver, W. (2002). Reliability and validity of a visual analog scale for acute abdominal pain in the ED. *The American Journal of Emergency Medicine*, 20(4), 287–290. <https://doi.org/10.1053/ajem.2002.33778>
- Hotfiel, T., Freiwald, J., Hoppe, M. W., Lutter, C., Forst, R., Grim, C., Bloch, W., Hüttel, M., & Heiss, R. (2018). Advances in delayed-onset muscle soreness (DOMS): Part I: pathogenesis and diagnostics. *Sportverletz Sportschaden*, 32(4), 243–250. <https://doi.org/10.1055/a-0753-1884>
- Ichihara, M., Sobue, S., Ito, M., Ito, M., Hirayama, M., & Ohno, K. (2015). Beneficial biological effects and the underlying mechanisms of molecular hydrogen - comprehensive review of 321 original articles. *Medical Gas Research*, 5(12), 1–21. <https://doi.org/10.1186/s13618-015-0035-1>
- Ito, M., Hirayama, M., Yamai, K., Goto, S., Ito, M., Ichihara, M., & Ohno, K. (2012). Drinking hydrogen water and intermittent hydrogen gas exposure, but not lactulose or continuous hydrogen gas exposure, prevent 6-hydroxydopamine-induced Parkinson's disease in rats. *Medical Gas Research*, 2(15), 1–7. <https://doi.org/10.1186/2045-9912-2-15>
- Kawamura, T., Gando, Y., Takahashi, M., Hara, R., Suzuki, K., & Muraoka, I. (2016). Effects of hydrogen bathing on exercise-induced oxidative stress and delayed-onset muscle soreness. *Japanese Journal of Physical Fitness and Sports Medicine*, 65(3), 297–305. <https://doi.org/10.7600/jspfsm.65.297>
- Kawamura, T., Higashida, K., & Muraoka, I. (2020). Application of molecular hydrogen as a novel antioxidant in sports science. *Oxidative Medicine and Cellular Longevity*, 2020, 1–7. <https://doi.org/10.1155/2020/2328768>
- Kawamura, T., Suzuki, K., Takahashi, M., Tomari, M., Hara, R., Gando, Y., & Muraoka, I. (2018). Involvement of neutrophil dynamics and function in exercise-induced muscle damage and delayed-onset muscle soreness: Effect of hydrogen bath. *Antioxidants*, 7, 1–13. <https://doi.org/10.3390/antiox7100127>
- Kelly, A. M. (2001). The minimum clinically significant difference in visual analogue scale pain score does not differ with severity of pain. *Emergency Medicine Journal*, 18(3), 205–207. <https://doi.org/10.1136/emj.18.3.205>
- Kregel, K. C., & Zhang, H. J. (2007). An integrated view of oxidative stress in aging: Basic mechanisms, functional effects, and pathological considerations. *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology*, 292(1), R18–R36. <https://doi.org/10.1152/ajpregu.00327.2006>
- Lorenzo-Martínez, M., Rey, E., & Padrón-Cabo, A. (2020). The effect of age on between-match physical performance variability in professional soccer players. *Research in Sports Medicine*, 28(3), 351–359. <https://doi.org/10.1080/15438627.2019.1680985>
- Nédélec, M., McCall, A., Carling, C., Legall, F., Berthoin, S., & Dupont, G. (2012). Recovery in soccer: Part I - post-match fatigue and time course of recovery. *Sports Medicine*, 42(12), 997–1015. <https://doi.org/10.2165/11635270-000000000-00000>
- Ohno, K., Ito, M., Ichihara, M., & Ito, M. (2012). Molecular hydrogen as an emerging therapeutic medical gas for neurodegenerative and other diseases. *Oxidative Medicine and Cellular Longevity*, 2012, 1–11. <https://doi.org/10.1155/2012/353152>
- Ohsawa, I., Ishikawa, M., Takahashi, K., Watanabe, M., Nishimaki, K., Yamagata, K., Katsura, K. I., Katayama, Y., Asoh, S., & Ohta, S. (2007). Hydrogen acts as a therapeutic antioxidant by selectively reducing cytotoxic oxygen radicals. *Nature Medicine*, 13(6), 688–694. <https://doi.org/10.1038/nm1577>
- Ohta, S. (2014). Molecular hydrogen as a preventive and therapeutic medical gas: Initiation, development and potential of hydrogen medicine. *Pharmacology & Therapeutics*, 144(1), 1–11. <https://doi.org/10.1016/j.pharmthera.2014.04.006>
- Ohta, S. (2023). Molecular hydrogen may activate the transcription factor Nrf2 to alleviate oxidative stress through the hydrogen-targeted porphyrin. *Aging Pathobiology and Therapeutics*, 5(1), 25–32. <https://doi.org/10.31491/APT.2023.03.104>

- Ostojic, S. M. (2015). Molecular hydrogen in sports medicine: New therapeutic perspectives. *International Journal of Sports Medicine*, 36(4), 273–279. <https://doi.org/10.1055/s-0034-1395509>
- Peake, J. M., Neubauer, O., Della Gatta, P. A., & Nosaka, K. (2017). Muscle damage and inflammation during recovery from exercise. *Journal of Applied Physiology*, 122(3), 559–570. <https://doi.org/10.1152/jappphysiol.00971.2016>
- Pyne, D. B. (1994). Exercise-induced muscle damage and inflammation: A review. *Australian Journal of Science and Medicine in Sport*, 26(3–4), 49–58.
- Radák, Z., Chung, H. Y., Naito, H., Takahashi, R., Jung, K. J., Kim, H. J., & Goto, S. (2004). Age-associated increase in oxidative stress and nuclear factor kappaB activation are attenuated in rat liver by regular exercise. *FASEB Journal*, 18(6), 749–750. <https://doi.org/10.1096/fj.03-0509fje>
- Sellami, M., Al-Muraikhy, S., Al-Jaber, H., Al-Amri, H., Al-Mansoori, L., Mazloun, N. A., Donati, F., Botre, F., & Elrayess, M. A. (2021). Age and sport intensity-dependent changes in cytokines and telomere length in elite athletes. *Antioxidants*, 10, 2–16. <https://doi.org/10.3390/antiox10071035>
- Shimouchi, A., Nose, K., Shirai, M., & Kondo, T. (2012). Estimation of molecular hydrogen consumption in the human whole body after the ingestion of hydrogen-rich water. *Advances in Experimental Medicine and Biology*, 737, 245–250. https://doi.org/10.1007/978-1-4614-1566-4_36
- Sim, M., Kim, C. S., Shon, W. J., Lee, Y. K., Choi, E. Y., & Shin, D. M. (2020). Hydrogen-rich water reduces inflammatory responses and prevents apoptosis of peripheral blood cells in healthy adults: A randomized, double-blind, controlled trial. *Scientific Reports*, 10, 1–10. <https://doi.org/10.1038/s41598-020-68930-2>
- Sládečková, B., Botek, M., Krejčí, J., Valenta, M., McKune, A., Neuls, F., & Klimešová, I. (2024). Hydrogen-rich water supplementation promotes muscle recovery after two strenuous training sessions performed on the same day in elite fin swimmers: Randomized, double-blind, placebo-controlled, crossover trial. *Frontiers in Physiology*, 15, 1–11. <https://doi.org/10.3389/fphys.2024.1321160>
- Slezak, J., & Kura, B. (Eds.). (2024). *Molecular hydrogen in health and disease*. Springer Nature Switzerland.
- Slezak, J., Kura, B., LeBaron, T. W., Singal, P. K., Buday, J., & Barancik, M. (2021). Oxidative stress and pathways of molecular hydrogen effects in medicine. *Current Pharmaceutical Design*, 27(5), 610–625. <https://doi.org/10.2174/1381612826666200821114016>
- Smith, L. L. (1991). Acute inflammation: The underlying mechanism in delayed onset muscle soreness? *Medicine and Science in Sports and Exercise*, 23(5), 542–551.
- Terrados, N., Mielgo-Ayuso, J., Deletrat, A., Ostojic, S. M., & Calleja-Gonzalez, J. (2019). Dietetic-nutritional, physical and physiological recovery methods post-competition in team sports. *Journal of Sports Medicine and Physical Fitness*, 59(3), 415–428. <https://doi.org/10.23736/S0022-4707.18.08169-0>
- Timón, R., Olcina, G., González-Custodio, A., Camacho-Cardenosa, M., Camacho-Cardenosa, A., & Martínez Guardado, I. (2021). Effects of 7-day intake of hydrogen-rich water on physical performance of trained and untrained subjects. *Biology of Sport*, 38(2), 269–275. <https://doi.org/10.5114/biolport.2020.98625>
- Toumi, H., & Best, T. M. (2003). The inflammatory response: Friend or enemy for muscle injury? *British Journal of Sports Medicine*, 37(4), 284–286. <https://doi.org/10.1136/bjsm.37.4.284>
- Wei, M., Liu, X., & Wang, S. (2025). The impact of various post-exercise interventions on the relief of delayed-onset muscle soreness: A randomized controlled trial. *Frontiers in Physiology*, 16, 1–15. <https://doi.org/10.3389/fphys.2025.1622377>
- Zhou, K., Liu, M., Wang, Y., Liu, H., Manor, B., Bao, D., Zhang, L., & Zhou, J. (2023). Effects of molecular hydrogen supplementation on fatigue and aerobic capacity in healthy adults: A systematic review and meta-analysis. *Frontiers in Nutrition*, 10, 1–18. <https://doi.org/10.3389/fnut.2023.1094767>