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Review Article

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Hydrogen-Rich Water and Molecular Hydrogen in Sports Science: A Review of Physiological Effects, Recovery Mechanisms, and Performance Outcomes

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ABSTRACT

Molecular hydrogen (H_2), particularly in the form of hydrogen-rich water (HRW), has gained increasing attention for its potential antioxidative, anti-inflammatory, and ergogenic properties in physically active populations. The aim of this narrative review was to synthesize and critically evaluate current evidence on the physiological effects, recovery mechanisms, and performance outcomes associated with molecular hydrogen supplementation in sport and exercise science. A literature search was conducted for studies published between 2000 and 2024 using PubMed, Scopus, Web of Science, and Google Scholar. The review included studies investigating the effects of H_2 administered via hydrogen-rich water, inhalation, or intravenous infusion on oxidative stress, inflammation, fatigue, and physical performance. Current evidence indicates that molecular hydrogen may attenuate exercise-induced oxidative stress, reduce inflammatory biomarkers, improve lactate metabolism, and alleviate delayed onset muscle soreness. Hydrogen-rich water appears to confer benefits in both acute and chronic exercise contexts; however, study findings remain heterogeneous. Molecular hydrogen shows potential as a supportive intervention in sports medicine and exercise recovery. Nevertheless, variability in study design, limited sample sizes, and inconsistent performance metrics restrict definitive conclusions. Further well-designed, large-scale randomized controlled trials are needed to establish optimal dosing, administration strategies, and long-term effectiveness.

Key Words: Molecular hydrogen, Hydrogen-rich water, Oxidative stress, Athletic recovery, Antioxidant therapy, Randomized controlled trials

INTRODUCTION

Molecular hydrogen (H_2) has recently emerged as a potential therapeutic and ergogenic agent within sports and exercise science. Its relevance stems primarily from its selective antioxidant properties, which may counteract the elevated production of reactive oxygen species (ROS) observed during strenuous or prolonged exercise. Increased ROS generation is a well-recognized consequence of intensified metabolic demand, can result in oxidative damage to muscle tissue, and impaired physiological functioning. [1,2] Molecular hydrogen is distinguished by its ability to selectively neutralize highly reactive species, including hydroxyl radicals and peroxynitrite, thereby contributing to the mitigation of exercise-induced oxidative stress.[3]

Beyond its antioxidative role, molecular hydrogen appears to influence inflammatory pathways. Several studies indicate that H_2 may modulate the expression of pro-inflammatory cytokines that typically rise following intensive training sessions.[4,5] This anti-inflammatory action may support faster tissue recovery and decrease the cumulative inflammatory burden associated with high-volume training.[6,7] By simultaneously targeting oxidative stress and inflammation—two central mechanisms contributing to exercise-induced fatigue—molecular hydrogen presents a physiologically plausible intervention for enhancing post-exercise recovery.[8,9]

Hydrogen-rich water (HRW) and inhaled hydrogen gas represent the most commonly investigated administration methods. HRW has been evaluated in multiple randomized controlled trials, with findings indicating possible improvements in oxidative biomarkers, lactate kinetics, and subjective fatigue responses across various exercise modalities.[10,11,12] These outcomes, although heterogeneous, suggest that HRW

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may serve as a practical adjunct to training, particularly in endurance-based or high-intensity exercise environments.[13-15]

A notable advantage of H_2 supplementation is its excellent safety profile. Available data indicate an absence of adverse effects at physiologically appropriate dosages.[16] Unlike some conventional antioxidant supplements—such as high-dose vitamins C and E—that may interfere with adaptive cellular responses to exercise, hydrogen appears to exert regulatory rather than suppressive effects on redox signaling pathways.[17,18] This characteristic strengthens the rationale for its potential integration into sports medicine and performance practice.

Although preliminary evidence supports the use of molecular hydrogen in exercise settings, current findings require cautious interpretation due to variability in study methodologies, inconsistent dosing protocols, and relatively small sample sizes. Further research is needed to clarify optimal administration strategies, identify population-specific responses, and determine the translational relevance of the observed biochemical effects. This review synthesizes contemporary evidence on the physiological, recovery-related, and performance-related outcomes associated with molecular hydrogen, with a particular emphasis on hydrogen-rich water in athletic and recreational populations.

MATERIALS AND METHODS

A narrative review methodology was employed to evaluate existing scientific literature concerning the physiological effects, recovery benefits, and performance implications of molecular hydrogen (H_2), with a specific emphasis on hydrogen-rich water (HRW) in sport and exercise contexts. A comprehensive search of PubMed, Scopus, Web of Science, and Google Scholar was conducted for studies published between 2000 and 2024. Search terms included “molecular hydrogen,” “hydrogen-rich water,” “exercise,” “oxidative stress,” “inflammation,” “athletic performance,” and “recovery.”

Eligible articles included peer-reviewed original studies, clinical trials, systematic reviews, and meta-analyses published in English and examining the effects of H_2 in healthy adults or athletes. Studies investigating acute or chronic interventions, and those utilizing oral, inhaled, or intravenous hydrogen administrations, were included. Extracted data encompassed study design, participant demographics, intervention duration and dosage, and outcome measures related to oxidative stress, inflammation, fatigue, and physical performance. Methodological quality was assessed descriptively, with particular attention to sample size, control conditions, blinding, and statistical rigor. Given the heterogeneity in study protocols, populations, and outcome measures, a qualitative synthesis was deemed more appropriate than meta-analysis.

RESULTS

Antioxidant and Anti-inflammatory Effects of Molecular Hydrogen

Across the reviewed studies, strenuous or prolonged physical activity was associated with increased metabolic demand and elevated formation of reactive oxygen species (ROS), resulting in subsequent oxidative stress.[19,20] Excessive ROS production can impair cellular homeostasis, damage biomolecules, and trigger inflammatory responses.[21] Although moderate exercise enhances endogenous antioxidant capacity, high-intensity or exhaustive exercise may exceed physiological buffering systems, contributing to muscle damage and temporary immunosuppression.[22-24] Key findings from the available studies on hydrogen supplementation are summarized in Table 1.

Exercise-induced oxidative stress negatively influences athletic performance by impairing muscle contractility, delaying recovery and exacerbating fatigue.[25-27] It is also linked to cognitive fatigue which may further compromise performance.[28,29] In contrast, regular moderate-intensity training improves antioxidant defense and promotes adaptive physiological responses.[30-32]

Multiple studies reported that molecular hydrogen supplementation reduced post-exercise biomarkers of oxidative stress and inflammation. A decrease in inflammatory markers, including C-reactive protein (CRP) and interleukin-6 (IL-6), were observed after H_2 administration.[33,34] Clinical findings also demonstrate reductions in oxidative damage biomarkers, such as 8-hydroxy-2′-deoxyguanosine (8-OHdG) following hydrogen inhalation.[35] Supplementation with hydrogen-rich water (HRW) has additionally been associated with lower perceived fatigue and reduced markers of muscle damage in trained individuals.[36]

Routes of administration influence the pharmacokinetics and physiological impact of hydrogen (see Table 2). Inhalation generates rapid increases in circulating hydrogen concentrations, leading to acute reductions in oxidative and inflammatory markers.[37-39] In contrast, HRW produces more gradual hydrogen availability yet provides sustained antioxidant effects suitable for daily use in athletic contexts.[40,41]

Effects on Performance, Recovery, and Fatigue

Growing interest in the potential ergogenic properties of molecular hydrogen has led to several studies examining its effects on exercise, performance and recovery. Reported outcomes suggest that H_2 may enhance performance by modulating oxidative stress pathways and improving metabolic efficiency during exercise.[42] HRW supplementation or use of wearable hydrogen-releasing devices have shown preliminary benefits in reducing muscle soreness, accelerating recovery, and improving endurance-based outcomes.[43-44]

Short-term HRW supplementation was associated with improved lactate dynamics and reduced ratings of perceived exertion.[45-46]

Evidence regarding HRW effects on anaerobic performance and resistance training is inconsistent. Findings from Aoki et al. indicate reductions in muscle fatigue in elite athletes, but replication across diverse populations is limited.[47]

DISCUSSION

The results indicate that molecular hydrogen supplementation may attenuate exercise-induced oxidative stress and inflammation, supporting its role as a selective antioxidant capable of selectively neutralizing highly reactive species while preserving essential physiological redox signaling.[48] Reductions in inflammatory and oxidative biomarkers suggest that hydrogen may help mitigate the cellular stress associated with high-intensity exercise, with potential implications for recovery and fatigue management.

Differences observed between administration routes highlight important practical considerations. Hydrogen inhalation appears to provide rapid antioxidant and anti-inflammatory effects, making it potentially more effective in acute therapeutic scenarios whereas, HRW offers sustained hydrogen availability and may be preferable for long-term supplementation strategies.[49,50]

The observed improvements in endurance-related outcomes, lactate dynamics, and reduced ratings of perceived exertion suggest that hydrogen may influence metabolic efficiency and recovery processes, potentially through effects on mitochondrial function and inflammatory signaling pathways. These mechanisms may support more efficient recovery between training sessions.[51,52]

Although HRW shows promise in endurance exercise, evidence related to its effects on anaerobic performance and resistance training remains inconsistent. The variability of study outcomes underscores the need for standardized protocols, larger sample sizes, and consistent performance metrics.

Beyond elite athletes, molecular hydrogen may also hold value for recreational athletes, older adults, and individuals with lower training tolerance, as oxidative stress plays a prominent role in fatigue and muscle soreness within these groups.[53] The potential integration of hydrogen-based interventions, such as HRW, into physical educational programs has been proposed as a strategy to support recovery and encourage sustained physical activity.[54]

Methodological Limitations and Future Directions

Despite promising findings, research on molecular hydrogen in sports science faces several methodological challenges. Many studies utilize small sample sizes, lack adequate control groups, or employ non-randomized designs, limiting the strength of conclusions. [55,56] Inconsistent performance metrics and heterogeneous intervention protocols further hinder cross-study comparisons.[30,31]

Future research should prioritize well-designed, adequately powered randomized controlled trials with standardized dosing regimens and clearly defined outcome measures. [17,30] Statistical rigor, including proper sample size estimation and bias mitigation strategies, is critical for producing reliable evidence.[17] Qualitative studies may also provide insights into subjective experiences, adherence, and practical considerations associated with H_2 supplementation.[18] Additionally, contextual factors—such as training environment, sport-specific demands, and individual variability—should be incorporated into study design to improve ecological validity.[3]

CONCLUSIONS

Molecular hydrogen, particularly in the form of hydrogen-rich water, represents a promising adjunct in sports science due to its antioxidative and anti-inflammatory properties. Current evidence suggests that H_2 may attenuate exercise-induced oxidative stress, reduce inflammatory biomarkers, mitigate delayed onset muscle soreness, and improve subjective fatigue. Although hydrogen inhalation appears effective for acute therapeutic applications, HRW offers a practical and well-tolerated option for daily use in physically active populations.

However, significant limitations in the existing literature—including small sample sizes, inconsistent methodologies, and a lack of standardized outcome measures—restrict the ability to draw definitive conclusions regarding optimal dosing or performance-enhancing effects. High quality randomized controlled trials and long-term studies are essential to clarify the role of molecular hydrogen within sports medicine and preventive health. While the current findings are encouraging, molecular hydrogen should be regarded as a promising yet still emerging modality requiring further validation.

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Conflicts of Interest

The authors declare that there are no conflicts of interest.

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Author Contributions

Julia Charkot: Conceptualization, methodology design, literature search, data extraction, and primary manuscript drafting.

Wojciech Jędrzej Bieńkowski: Critical review of the literature, data interpretation, preparation of tables, and contribution to manuscript revision.

Katarzyna Bielawska: Supervision of scientific accuracy, refinement of the discussion section, editing for coherence, and final content validation.

Mikołaj Charkot: Assistance with literature screening, reference organization, and formatting of the manuscript according to journal guidelines.

Michał Bieńkowski: Technical review of statistical and methodological aspects, improvement of structure and flow, and final proofreading of the manuscript.

Ethical Approval

Ethical approval was not required for this study as it is a narrative review and does not involve human or animal subjects.

Informed Consent

Informed consent was not applicable for this study, as it did not involve human participants.

REFERENCES

1. Alharbi AAD, Alhussain MH, Alharthi AS, Alshahrani MS, Alqarni A. Application of Molecular Hydrogen as an Antioxidant in Responses to Ventilatory and Ergogenic Adjustments During Incremental Exercise in Humans. Nutrients. 2021;13(2):459. doi: 10.3390/nu13020459. Accessed on: 16 September 2025; 20:00.
2. Alharbi AAD, Alhussain MH, Alharthi AS, Alshahrani MS, Alqarni A. The Acute Effects of a Single Dose of Molecular Hydrogen Supplements on Responses to Ergogenic Adjustments During High-Intensity Intermittent Exercise in Humans. Nutrients. 2022;14(19):3974. doi: 10.3390/nu14193974. Accessed on: 16 September 2025; 20:00.
3. LeBaron TW, Laher I, Kura B, Slezak J. Hydrogen Gas: From Clinical Medicine to an Emerging Ergogenic Molecule for Sports Athletes. Can J Physiol Pharmacol. 2019 Sep;97(9):797–807. doi: 10.1139/cjpp-2019-0067. Accessed on: 16 September 2025; 20:00.
4. Aoki KC, Nakao A, Adachi T, Matsui Y, Miyakawa S. Pilot Study: Effects of Drinking Hydrogen-Rich Water on Muscle Fatigue Caused by Acute Exercise in Elite Athletes. Med Gas Res. 2012;2(1):12. doi: 10.1186/2045-9912-2-12. Accessed on: 16 September 2025; 20:00.
5. Bhatt A, Jain A, Bhatnagar S, Gupta S. Assessment of the Effects of Hydrogen Water on Human Gingival Fibroblast Cell Culture in Patients With Chronic Periodontitis. J Indian Soc Periodontol. 2023;27(3):278–282. doi: 10.4103/jisp.jisp_546_21. Accessed on: 16 September 2025; 20:00.
6. Botek M, Krejčí J, Valenta M, McKune AJ. Hydrogen-Rich Water Supplementation and Up-Hill Running Performance: Effect of Athlete Performance Level. Int J Sports Physiol Perform. 2020;15(8):1193–1196. doi: 10.1123/ijspp.2019-0507. Accessed on: 16 September 2025; 20:00.
7. Botek M, Krejčí J, McKune AJ, Sládečková B, Gába A, Valenta M, et al. Hydrogen Rich Water Consumption Positively Affects Muscle Performance, Lactate Response, and Alleviates Delayed Onset of Muscle Soreness After Resistance Training. J Strength Cond Res. 2021;36(10):2792–2799. doi: 10.1519/JSC.0000000000003979. Accessed on: 16 September 2025; 20:00.
8. Brisebois M, Kearney S, Taylor K, Holt C, Slater G, Burke L, et al. Dietary Practices and Supplement Use Among CrossFit Participants. J Int Soc Sports Nutr. 2022;19(1):316–335. doi: 10.1080/15502783.2022.2086016. Accessed on: 16 September 2025; 20:00.
9. Ceylan HI. Nutritional Strategies for Peak Performance: Guidelines for Athletes' Optimal Fueling and Recovery. HN. 2023;1(4):90–98. doi: 10.61838/kman.hn.1.4.11. Accessed on: 16 September 2025; 20:00.
10. Chalari E, Deli CK, Jamurtas AZ, Koutedakis Y, Fatouros IG, Veskoukis AS, et al. The Impact of High-Intensity Interval Exercise Including Acceleration/Deceleration Patterns on Redox Status of Healthy Male Adults. Appl Sci. 2024;14(6):2655. doi: 10.3390/app14062655. Accessed on: 16 September 2025; 20:00.
11. Chmielewska A, Regulska-Ilow B. Evaluation of Supplement Use in Sport Climbers at Different Climbing Levels. Nutrients. 2022;15(1):100. doi: 10.3390/nu15010100. Accessed on: 16 September 2025; 20:00.
12. D'Angelo S. Polyphenols and Athletic Performance: A Review on Human Data. 2019. doi: 10.5772/intechopen.85031. Accessed on: 16 September 2025; 20:00.
13. Debevec T, Millet GP, Pialoux V. Hypoxia-Induced Oxidative Stress Modulation With Physical Activity. Front Physiol. 2017;8:84. doi: 10.3389/fphys.2017.00084. Accessed on: 16 September 2025; 20:00.
14. Dewangga MW, Irianto DP. The Differences Frequency of Weekly Physical Exercise in Antioxidant Serum Levels and Muscle Damage. Fizjoterapia Polska. 2023;23(2):112–120. doi: 10.56984/8zg0dfb15. Accessed on: 16 September 2025; 20:00.
15. Díaz-Castro J, Guisado R, Kajarabille N, López-Frías M, Ochoa JJ. *Phlebodium Decumanum* Ameliorates Oxidative Stress and Inflammatory Signaling Induced by Strenuous Exercise. Eur J Appl Physiol. 2012;112(8):3119–3128. doi: 10.1007/s00421-011-2295-3. Accessed on: 16 September 2025; 20:00.
16. Dixon B, Tang J, Zhang JH. The Evolution of Molecular Hydrogen: A Noteworthy Potential Therapy with Clinical Significance. Med Gas Res. 2013;3(1):10. doi: 10.1186/2045-9912-3-10. Accessed on: 16 September 2025; 20:00.
17. Halperin I, Vigotsky AD, Foster C, Pyne DB, McGuigan MR, Coutts AJ, et al.Strengthening the Practice of Exercise and Sport-Science Research. Int J Sports Physiol Perform. 2018;13(2):127–134. doi: 10.1123/ijspp.2017-0322. Accessed on: 16 September 2025; 20:00.
18. Harper LD, McCunn R. "Hand in Glove": Using Qualitative Methods to Connect Research and Practice. Int J Sports Physiol Perform. 2017;12(7):990–993. doi: 10.1123/ijspp.2017-0081. Accessed on: 16 September 2025; 20:00.

19. Hori A, Ohno K, Miwa M, Shibata S, Nakao A. Two-Week Hydrogen-Rich Water Supplementation Increases Peak VO_2 During Incremental Cycling Exercise. Med Gas Res. 2020;10(4):163. doi: 10.4103/2045-9912.304223. Accessed on: 16 September 2025; 20:00.
20. Jebabli N, Abdelmalek M, Elloumi M, Chamari K. Acute Effect of Hydrogen-Rich Water on Physical, Perceptual and Cardiac Responses During Aerobic and Anaerobic Exercises. Front Physiol. 2023;14:1240871. doi: 10.3389/fphys.2023.1240871. Accessed on: 16 September 2025; 20:00.
21. Jin CH, Paik IY, Kwak YS, Kim KB, Kim MH. Exhaustive Submaximal Endurance and Resistance Exercise Induce Temporary Immunosuppression via Oxidative Stress. J Exerc Rehabil. 2015;11(4):198–203. doi: 10.12965/jer.150221. Accessed on: 16 September 2025; 20:00.
22. Juesas Á, Santos-Lozano A, Pareja-Galeano H, Sanchis-Gomar F, Lucia A. Effects of Elastic Band Training and Curcumin on Neuro-Oxidative Health in Older Adults. Healthcare. 2025;13(9):1055. doi: 10.3390/healthcare13091055. Accessed on: 16 September 2025; 20:00.
23. Kawamura T, Higashida K, Muraoka I. Application of Molecular Hydrogen as a Novel Antioxidant in Sports Science. Oxid Med Cell Longev. 2020;2020:2328768. doi: 10.1155/2020/2328768. Accessed on: 16 September 2025; 20:00.
24. Koyama K, Yamamoto K, Nakao A, Ohsawa I, Ishikawa M. Hydrogen-Rich Gas Mixture Inhalation During Recovery Reduces Oxidative Stress and Muscle Damage. Med Gas Res. 2020;10(4):155. doi: 10.4103/2045-9912.304222. Accessed on: 16 September 2025; 20:00.
25. Kwon H. Hydrogen's Antiaging and Whitening Effects on Skin. Turcomat. 2021;12(5):369–374. doi: 10.17762/turcomat.v12i5.963. Accessed on: 16 September 2025; 20:00.
26. LeBaron TW, Larson A, Ohno K, Gojkovic S. Acute Supplementation with Molecular Hydrogen Benefits Submaximal Exercise Indices. J Lifestyle Med. 2019;9(1):36–43. doi: 10.15280/jlm.2019.9.1.36. Accessed on: 16 September 2025; 20:00.
27. Li Y, Liu X, Zhang Y, Wang J, Chen H. Can Molecular Hydrogen Supplementation Reduce Exercise-Induced Oxidative Stress? Front Nutr. 2024;11:1328705. doi: 10.3389/fnut.2024.1328705. Accessed on: 16 September 2025; 20:00.
28. Liu W, Sun X, Huang J. Hydrogen Inhalation Improves Neurological Outcomes After Cerebral Ischemia/Reperfusion. Med Gas Res. 2018;8(1):1. doi: 10.4103/2045-9912.229596. Accessed on: 16 September 2025; 20:00.
29. Manaenko A, Lekic T, Sozen T, Martin R, Tang J, Zhang JH, et al. Hydrogen Inhalation Is Neuroprotective After Intracerebral Hemorrhage. 2011. doi: 10.1007/978-3-7091-0693-8_30. Accessed on: 16 September 2025; 20:00.
30. McLean S, McAuley AB, Ploutz-Snyder L. A Systems Analysis Critique of Sport-Science Research. Int J Sports Physiol Perform. 2021;16(10):1385–1392. doi: 10.1123/ijspp.2020-0934. Accessed on: 16 September 2025; 20:00.
31. Mesquida C, Dekerle J, Atkinson G. Replication Concerns in Sports and Exercise Science. R Soc Open Sci. 2022;9(12):220946. doi: 10.1098/rsos.220946. Accessed on: 16 September 2025; 20:00.
32. Militello R, Zampogna E, Carraro E. Physical Activity and Oxidative Stress in Aging. 2024. doi: 10.20944/preprints202404.0293.v1. Accessed on: 16 September 2025; 20:00.
33. Munther S. Effects of Cigarette Smoking and Exercise on Salivary Antioxidant Activity. Saudi Dent J. 2019; 31(1):31–38. doi: 10.1016/j.sdentj.2018.09.002. Accessed on: 16 September 2025; 20:00.
34. Ostojić SM. Molecular Hydrogen in Sports Medicine: New Therapeutic Perspectives. Int J Sports Med. 2014;36(4):273–279. doi: 10.1055/s-0034-1395509. Accessed on: 16 September 2025; 20:00.
35. Othman KR, Ahmad S, Hussain Z. Dietary Supplement Enriched in Antioxidants and Omega-3 Protects From Retinal Degeneration. PLoS One. 2015;10(6):e0128395. doi: 10.1371/journal.pone.0128395. Accessed on: 16 September 2025; 20:00.
36. Poucher ZA, Tamminen KA, Caron JG, Sweet SN. Designing Qualitative Research Studies in Sport Psychology. Int Rev Sport Exerc Psychol. 2019;13(1):163–186. doi: 10.1080/1750984X.2019.1656276. Accessed on: 16 September 2025; 20:00.
37. Prasertsri P, Boonla O. Resistance Training vs HIIT on Oxidative Stress Markers. J Exerc Rehabil. 2021;17(3):198–206. doi: 10.12965/jer.2142184.092. Accessed on: 16 September 2025; 20:00.
38. Rojas-Valverde D, Sanchez-Urena B, Gutierrez-Vargas R. New Technologies and Statistical Models in Sports Science. Front Sports Act Living. 2023;5:1267548. doi: 10.3389/fspor.2023.1267548. Accessed on: 16 September 2025; 20:00.
39. Sarmiento A, Díaz-Castro J, Pulido-Morán M. Short-term Ubiquinol Supplementation Reduces Oxidative Stress. Biofactors. 2016;42(6):612–622. doi: 10.1002/biof.1297. Accessed on: 16 September 2025; 20:00.
40. Shen M, Zhang H, Yu H. Hydrogen as a Therapeutic Agent in Critical Care. Med Gas Res. 2014;4(1):17. doi: 10.1186/2045-9912-4-17. Accessed on: 16 September 2025; 20:00.
41. Simatupang N, Sitompul A, Sinaga FA. Effects of Sport Massage in Preventing Decreased Immunity after Exercise. 2020. doi: 10.2991/ahsr.k.200305.008. Accessed on: 16 September 2025; 20:00.
42. Sundararajan P. Systematic Review of Molecular Hydrogen During Exercise. J Int Foot Ankle Found. 2022;1(7). doi: 10.55067/jifaf.v1i7.21. Accessed on: 16 September 2025; 20:00.
43. Timón R, Olcina G, González-Custodio A. Effects of 7-Day Intake of Hydrogen-Rich Water on Physical Performance. Biol Sport. 2021;38(2):269–275. doi: 10.5114/biolsport.2020.98625. Accessed on: 16 September 2025; 20:00.
44. Yamazaki M, Aoki K, Nakao A. Intravenous H_2-Saline Suppresses Oxidative Stress in Thoroughbred Horses. Sci Rep. 2015; 5:15514. doi: 10.1038/srep15514. Accessed on: 16 September 2025; 20:00.
45. Yatabe K, Yamazaki Y, Takahashi T. Effects of Different Exercise Conditions on Antioxidant Potential. Sports. 2021;9(3):36. doi: 10.3390/sports9030036. Accessed on: 16 September 2025; 20:00.
46. Yeo S, Davidge ST. Exercise, oxidative stress, and preeclampsia. J Womens Health. 2001;10:983-989. doi:10.1089/152460901317193558.
47. Zhao Y, Wang H, Fan Y. Hydrogen Gas Inhalation Prior to High-Intensity Training Reduces Attenuation of Nitric Oxide Bioavailability. Peer J. 2024;12:e18503. doi: 10.7717/peerj.18503. Accessed on: 16 September 2025; 20:00.
48. Morillas-Ruiz JM, Hernández-Sánchez P. Oxidative Stress and Antioxidant Defenses Induced by Physical Exercise. 2015. doi: 10.5772/61547. Accessed on: 16 September 2025; 20:00.
49. Sire AD, Liguori I, Russo G. Physical Rehabilitation and Bone Biomarkers in Breast Cancer Survivors. Int J Mol Sci. 2023;24(2):921. doi: 10.3390/ijms24020921. Accessed on: 16 September 2025; 20:00.
50. Squillacioti G, Rende R, Cione E. Non-Invasive Measurement of Exercise-Induced Oxidative Stress. Antioxidants. 2021;10(12):2008. doi: 10.3390/antiox10122008. Accessed on: 16 September 2025; 20:00.

51. Yona T, Wilson C, Prince F. Scoping Review of Statistical Parametric Mapping in Lower Limb Biomechanics. 2023. doi: 10.1101/2023.08.06.23293709. Accessed on: 16 September 2025; 20:00.
52. Zhang N, Zhang L, Zhang L. Hydrogen Gas Attenuates Airway Inflammation and Oxidative Stress in Asthmatic Mice. Asthma Res Pract. 2018;4(1):4. doi: 10.1186/s40733-018-0040-y. Accessed on: 16 September 2025; 20:00.
53. Zhou K, Shang Z, Li Y, Wang J, Chen H. Can Molecular Hydrogen Enhance Physical Performance? Front Nutr. 2024;11:1387657. doi: 10.3389/fnut.2024.1387657. Accessed on: 16 September 2025; 20:00.
54. Zhou K, Yuan C, Wang J. Effects of 8 Days Intake of Hydrogen-Rich Water on Muscular Endurance and Fatigue Recovery. Front Physiol. 2024; 15:1458882. doi: 10.3389/fphys.2024.1458882. Accessed on: 16 September 2025; 20:00.
55. Zhou Q, Chen Y, Li J, Liu X, Wang Y, Zhang H, et al. Hydrogen-Rich Water to Enhance Exercise Performance: A Review of Effects and Mechanisms. Metabolites. 2024;14(10):537. doi: 10.3390/metabo14100537. Accessed on: 16 September 2025; 20:00.
56. Zhuang K, Zhang J, Huang L. Hydrogen Inhalation Attenuates Oxidative Stress–Related Endothelial Injury after Subarachnoid Hemorrhage. Front Neurosci. 2020; 13:1441. doi: 10.3389/fnins.2019.01441. Accessed on: 16 September 2025; 20:00.

TABLE 1: Summary of Studies Investigating Molecular Hydrogen in Exercise and Recovery

Author (Year)	Population	H_2 Administration	Duration	Key Outcomes	Overall Conclusion
Aoki et al. (2012)	Elite athletes	HRW (oral)	Single dose	↓ oxidative stress markers, ↓ muscle fatigue	HRW improves acute recovery after high-intensity exercise
Botek et al. (2020)	Competitive runners	HRW (oral)	2 weeks	↑ uphill running performance	Possible ergogenic effect in endurance athletes
Botek et al. (2021)	Trained individuals	HRW (oral)	Acute	↓ DOMS, improved muscle performance	HRW may support resistance training recovery
Jebabli et al. (2023)	Recreational athletes	HRW (oral)	Single dose	↓ perceived exertion, ↓ HR, improved aerobic and anaerobic performance	HRW may acutely enhance exercise tolerance
Hori et al. (2020)	Healthy adults	HRW (oral)	2 weeks	↑ peak VO_2, improved cycling performance	HRW may enhance aerobic capacity
Zhou et al. (2024)	Trained adults	HRW (oral)	8 days	↑ muscular endurance, ↑ fatigue recovery	HRW beneficial for repeated resistance exercise
Zhou Q. et al. (2024)	Healthy adults	HRW (oral)	Various protocols	Improved lactate dynamics, ↓ fatigue markers	HRW may enhance metabolic efficiency
Zhao et al. (2024)	Rugby athletes	Inhalation	Acute	↓ 8-OHdG, preserved NO bioavailability	Hydrogen gas may reduce oxidative damage

TABLE 2: Comparison of Hydrogen Administration Methods in Sports and Exercise

Method	Hydrogen Availability	Time to Peak Effect	Best Use Case	Advantages	Limitations
Hydrogen-rich water (HRW)	Moderate	Slow–moderate	Daily supplementation for training and recovery	Safe, inexpensive, easy to use	Lower peak concentrations; requires regular intake
Inhalation	High	Rapid (minutes)	Acute recovery, high oxidative stress states	Strongest immediate effect, high bioavailability	Requires equipment; less practical for field use
Intravenous hydrogen saline	Very high	Immediate	Clinical or research settings	Precise dosing, rapid action	Not practical or allowed in sports settings; invasive